

3 1761 04213 0922

The Organized Science Series.

FIRST STAGE
MAGNETISM & ELECTRICITY



The Organized Science Series.

SCIENCE AND ART EXAMINATIONS

(BOARD OF EDUCATION).

FIRST STAGE.

I.—Practical Plane and Solid Geometry, First Stage.

By G. F. BURN. *Second Edition.* 2s.

“Written both with knowledge of the subject, and with appreciation of the difficulty of beginners.”—*School World.*

III.—Building Construction, First Stage. By BRYSSON

CUNNINGHAM, B.E., Assoc.M.Inst.C.E. *Second Edition, Revised and Enlarged.* 2s. 6d.

“This book accurately fulfils its purpose. The information it supplies is clearly set forth.”—*Builders' Journal.*

V.—Mathematics, First Stage. Containing all the Algebra

and Euclid required. Edited by Dr. WM. BRIGGS, M.A., B.Sc. F.R.A.S. 2s.

“Candidates cannot but find the book thoroughly useful.”—*Guardian.*

VIA.—Mechanics (Solids), First Stage. By F. ROSENBERG,

M.A., B.Sc. *Fifth Edition.* 2s.

“Meets most creditably the requirements of the syllabus.”—*Schoolmaster.*

VIB.—Mechanics of Fluids, First Stage. By G. H. BRYAN,

Sc.D., F.R.S., and F. ROSENBERG, M.A., B.Sc. *Second Edition.* 2s.

“Seems to be excellently adapted to its purpose.”—*Educational Times.*

VIII.—Sound, Light, and Heat, First Stage. By JOHN

DON, M.A., B.Sc. 2s.

“A thoroughly practical book.”—*London Teacher.*

IX.—Magnetism and Electricity, First Stage. By R. H.

JUDE, M.A. D.Sc. *New Edition, Revised.* 2s.

“As a first course on magnetism and electricity the book should prove serviceable.”—*Nature.*

X.—Inorganic Chemistry (Theoretical), First Stage.

By G. H. BAILEY, D.Sc., Ph.D. Heidelberg. Edited by Dr.

WM. BRIGGS, M.A., B.Sc., F.C.S. *Third Edition, Revised and Enlarged.* 2s.

“Probably the best systematic introduction to chemistry yet published.”—*Pharmaceutical Journal.*

UNIVERSITY TUTORIAL PRESS,

SCIENCE AND ART EXAMINATIONS

(BOARD OF EDUCATION).

FIRST STAGE.

Xp.—Inorganic Chemistry (Practical), First Stage. By F. BEDDOW, Ph.D., D.Sc. *Second Edition.* 1s.

"Dr. Beddow's useful manual fully meets the syllabus."—*Guardian.*

XIp.—Organic Chemistry, Practical. By G. GEORGE, F.C.S. 1s. 6d.

"The arrangement of the matter is carried out with considerable skill. We strongly recommend the book."—*Educational News.*

XIV.—Human Physiology, First Stage. By G. N. MEACHEN, M.D., B.S. Lond., L.R.C.P., M.R.C.S. 2s.

"A plain, clear, and sensible introduction to the study of human physiology from the hand of a thoroughly competent man."—*School Guardian.*

XV.—First Stage Biology (Section One). By W. S. FURNEAUX. 2s.

XVII.—Botany, First Stage. By A. J. EWART, D.Sc. *Second Edition.* 2s.

"An introductory text-book of first-rate quality."—*School Guardian.*

XX. & XXIs.—Modern Navigation (for the First and Second Stages). By WILLIAM HALL, B.A., R.N. 6s. 6d.

"A sound and trustworthy exposition of the subject."—*School World.*

XXII.—Steam, First Stage. By J. W. HAYWARD, M.Sc.

"The author is very happy in the treatment of this subject. The book is sure to give satisfaction wherever used."—*Nature.*

XXIII.—Physiography, First Stage. By A. M. DAVIES, B.Sc., F.G.S. 2s.

"This volume, admirably written and well illustrated, will form one of the best text-books for the examination."—*Teachers' Monthly.*

XXIII.—First Stage Physiography (Section One). Edited by R. WALLACE STEWART, D.Sc. Lond. 2s.

"A most admirable volume."—*Nature.*

XXV.—Hygiene, First Stage. By R. A. LYSTER, M.B., B.Sc., D.P.H. *Fourth Edition.* 2s.

"The work is well arranged, intelligibly expressed, and well illustrated, and can certainly be commended."—*Morning Post.*

XXVI.—Elementary Science of Common Life (Chemistry). By W. T. BOONE, B.A., B.Sc. 2s.

The Organized Science Series.

General Editor:

WILLIAM BRIGGS, LL.D., D.C.L., M.A., B.Sc.,

PRINCIPAL OF UNIVERSITY CORRESPONDENCE COLLEGE.

FIRST STAGE
MAGNETISM & ELECTRICITY.

LONDON: W. B. ELLIS, 121 GUY'S LANE, W.C.

The Organized Science Series :
FOR THE SCIENCE AND ART EXAMINATIONS
OF THE
BOARD OF EDUCATION.

GENERAL EDITOR—WM. BRIGGS, LL.D., D.C.L., M.A., B.Sc.

FOR THE FIRST STAGE.

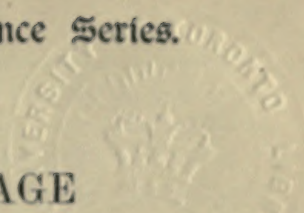
- I. First Stage Practical Plane and Solid Geometry. *Second Edition.* 2s.
III. First Stage Building Construction. *Second Edition, Revised and Enlarged.* 2s. 6d.
V. First Stage Mathematics (Euclid and Algebra). 2s.
VI.A. First Stage Mechanics of Solids. *Fifth Edition.* 2s.
VI.B. First Stage Mechanics of Fluids. *Second Edition.* 2s.
VIII. First Stage Sound, Light, and Heat. 2s.
IX. First Stage Magnetism and Electricity. *Revised Edition.* 2s.
X. First Stage Inorganic Chemistry (Theoretical). 2s.
XIV. First Stage Human Physiology. 2s.
XV. First Stage Biology (Section I.). 2s.
XVII. First Stage Botany. *Second Edition.* 2s.
XX. and XXI.B. Modern Navigation. 6s. 6d.
XXII. First Stage Steam. 2s.
XXIII. First Stage Physiography (Section I.). 2s.
XXIII. First Stage Physiography (Whole). 2s.
XXV. First Stage Hygiene. *Fourth Edition.* 2s.
XXVI. Elementary Science of Common Life (Chemistry). 2s.

X.P. First Stage Inorganic Chemistry (Practical). *Second Ed.* 1s.
XI.P. Systematic Practical Organic Chemistry. 1s. 6d.
-

LONDON: W. B. CLIVE, 157 DRURY LANE, W.C.

Physics
Electromagnetism

The Organized Science Series.



FIRST STAGE MAGNETISM & ELECTRICITY.

(Treated from the standpoint of Potential and Potential-Gradient.)

BY

R. H. JUDE, M.A. (CANTAB.), D.Sc. (LONDON),

HEAD OF THE MATHEMATICAL AND PHYSICAL DEPARTMENT, RUTHERFORD COLLEGE,
NEWCASTLE-ON-TYNE.

(New Edition, Revised and Re-written.)



82935-
11/5/07

LONDON: W. B. CLIVE,

University Tutorial Press Ltd

(University Correspondence College Press),

157 DRURY LANE, W.C.

1905.

Digitized by the Internet Archive
in 2007 with funding from
Microsoft Corporation

PREFACE.

THE first Edition of this book (published in 1898), which has now been through four impressions, was a somewhat novel departure in elementary works, inasmuch as in the treatment of Electrostatics it introduced the important conception of *Potential* very early, and aimed at leading the student to view phenomena from this standpoint rather than from the antiquated and misleading one of "free and bound" charges which had been gradually abandoned by scientific men, but found a persistent lodgment in the majority of our Secondary and Technical Schools.

The present Edition has been entirely recast. The following are the chief respects in which it differs from its predecessors :—

1. Part I. (Electrostatics), while still following the "Potential" method of treatment, has been considerably curtailed and simplified.

2. In Part II. (Magnetism) a brief account has been given of *Tubes of Force*, *Magnetic Flux*, *Permeability*, and *Reluctance*. These are not usually introduced into elementary books, but on account of their importance in Electrical

Engineering, in connexion with which at the present day so many take up the study of Electricity, it has been thought advisable to include them.

3. In Part III. (Voltaic Electricity) a great deal of comparatively unimportant theoretical matter has been omitted, and in its place considerable stress has been laid on such subjects as the energy in a circuit, which have a close bearing on the requirements of the young Engineer.

R. H. JUDE.

RUTHERFORD COLLEGE, NEWCASTLE-ON-TYNE,

January, 1904

TABLE OF CONTENTS.

PART I. FRICTIONAL ELECTRICITY, OR ELECTROSTATICS.

	PAGE
Chapter I. ELECTRIFICATION	1
Chapter II. POTENTIAL	23
Chapter III. POTENTIAL (<i>continued</i>) AND POTENTIAL-GRADIENT	46
Chapter IV. DISTRIBUTION OF ELECTRICITY ON CONDUCTORS	72
Chapter V. ELECTRICAL MACHINES AND CONDENSERS ...	81

PART II. MAGNETISM.

Chapter I. GENERAL PHENOMENA	92
Chapter II. NATURE OF MAGNETISM	104
Chapter III. MAGNETIC FIELD, FORCE, AND FLUX ...	120
Chapter IV. TERRESTRIAL MAGNETISM	140

PART III. VOLTAIC ELECTRICITY, OR ELECTRODYNAMICS.

Chapter I. GENERAL FACTS AND PRINCIPLES	162
Chapter II. VOLTAIC CELLS AND BATTERIES	186
Chapter III. ENERGY AND HEATING EFFECTS OF THE CURRENT	202
Chapter IV. CHEMICAL EFFECTS OF THE CURRENT ...	211
Chapter V. ELECTROMAGNETISM	220

ANSWER TO THE EXERCISES	239
INDEX	251
EXAMINATION PAPERS	256

The importance and specific purpose of the various portions of this book are indicated by the use of different types in accordance with the following scheme :—

Those of primary importance for the Board of Education First Stage Examination. } *Large Print.*

Those required for the Examination, but of somewhat minor importance. } *Small Print.*

Those of great importance *in themselves*, especially to the student of Electrical Engineering, and which will help to give a better grasp of the Board of Education Examination, but not officially prescribed. } *Small Print, and marked with an Asterisk.*

N.B.—Nearly all the Exercises except those marked with an asterisk have been set in recent years at the Board of Education First Stage Examination. In a few of special importance the year is prefixed thus (1903).

FIRST STAGE

ELECTRICITY AND MAGNETISM.

PART I.

FRICTIONAL ELECTRICITY OR ELECTROSTATICS.

CHAPTER I.

ELECTRIFICATION.

1. Fundamental Facts. If a piece of sealing-wax be rubbed with dry flannel or cloth, and then held near some small scraps of paper, or any light bodies such as feathers, bits of cotton-wool, etc., these will jump up to it. The sealing-wax therefore exerts a force tending to pull those bodies towards it; a force which does this is called an *attraction* or an *attractive force*, and the sealing-wax is said to *attract* the paper, etc. There are plenty of things that will produce this effect as well as, or even better than sealing-wax: a piece of brown paper after being well dried by holding before the fire and then rubbed with dry flannel will do it very well indeed. The first thing that was ever known to possess this property was *amber*; this fact was discovered about the year 600 B.C. by one Thales of Miletus, but it was not until the time of Queen Elizabeth that it was found out that many other things would behave in the same way: this was done by her physician Dr. Gilbert.

A warm dry glass rod, after being rubbed with silk, shows the effect very well, and a dry *ebonite* rod rubbed with fur does so still better: with this we can lift fairly large pieces of paper, cork, etc.

It is well not to confuse between the *force* of attraction and the *movement* of the attracted bodies: thus, if a small piece of cork be held in the fingers, and an ebonite rod rubbed with fur be placed two or three inches from it, the cork, of course, cannot move because it is held fast; but the rod is attracting it all the same. If the rod be

held over a heavy body, such as an iron or wooden bar, the latter is not lifted simply because the attractive force is not strong enough to overcome its weight ; but it is only necessary to balance the bar on



Fig. 1.

a pivot as in fig. 1, or a stirrup as in fig. 2, and hold the rubbed ebonite rod a few inches from it towards its side, when it moves readily towards it.

2. Electrification. Whenever a body shows this power of attracting things it is said to be *electrified*, or to possess an *electrification*. It is also said to be *charged*, or to possess a *charge*. The two latter terms will be assigned a more definite meaning in § 26. Bodies in their ordinary state do not, of course, exhibit this property ; such are said to be *neutral*. Hence the general facts of § 1 may be summed up in the statement that *electrified bodies attract neutral ones*.

3. All Forces are Mutual. It will help us to avoid mistakes to notice that *all forces are mutual*. This principle is a mechanical one, and applies to all kinds of forces. Thus a horse exerts a certain forward pull on a cart, and *the cart exerts a precisely equal backward pull upon the horse*. An electrified body attracts a neutral one, and *the neutral one attracts the electrified one with an equal force*. In the preceding experiments matters are so arranged that the neutral one is free to move while the electrified one is held fast, but it is easy to arrange them the other way ; thus, if an electrified ebonite rod be balanced on a pivot, and a neutral wooden one held in the hand near it, the ebonite will move up to the wood.

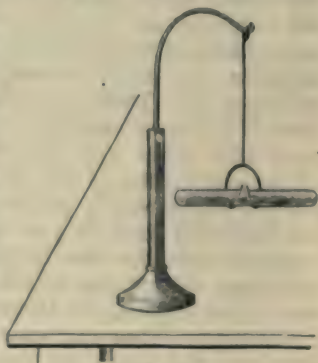


Fig. 2.

4. Electricity. Now, when it was discovered that so many things could be electrified, men asked *why* it was ; and they began to make

out several theories. But they really had not enough facts to build a theory upon; and, even now that very much more is known, scientific men are not certain as to the cause of electrification. But we are sure that there must be *something* which is *somehow* or *other* affected in such a way as to produce the attraction, and to that *something* we give the name *electricity*.

We must be very careful not to confuse between electricity and electrification. "Electrification" is merely a name given to the *condition of the electrified body*, while "electricity" is the mysterious "*something*" which renders it possible to produce that condition. Nobody knows for certain what electricity is, or what happens to the electricity when a body is electrified, though on this latter point we shall see, as we go on, we can make a very reasonable supposition (§ 26).

One thing, however, we must guard against from the beginning; we must never suppose that when we electrify a body we *make any electricity*; it is much more likely that we only alter the condition of what already exists, so that it can do what it could not do before,—in something the same way as, when we wind up a watch, we do not *make* the spring, we merely alter the arrangement of its coils, and then it can do what it could not do before—viz., make the watch "go."

5. Induction. In § 2 we have said that "electrified bodies attract neutral ones." But here a question arises. A piece of cork is lying on the table: it is "neutral." We then bring over it an electrified rod, and it is attracted. *Is the cork neutral while the rod is near it but not actually touching it?* This question can be answered only by experiment; and we shall learn in the next chapter that the cork is certainly *not* neutral, but that it becomes electrified by the *external influence of the electrified rod*.

Such electrification is called *induced* electrification, or electrification by *induction*. The same is true in every case: the attracted body, which we say is neutral, is really not so, but is electrified by induction. When, therefore, we say that an electrified body attracts a neutral one, what we mean is, not that the latter is actually neutral *while it is being attracted*, but that *it would be neutral but for the presence of the attracting body*.

We shall deal more particularly with induced electrifications in the next chapter. An electrification which is not the mere result of

external influence, but, so to speak, belongs properly to the body considered, is sometimes spoken of as a *free electrification*, or a *free charge*: such is the charge imparted to a body by rubbing. In general, when we speak of "electrification" or "charge," we mean it to be free, unless the contrary is specified.

6. Pith-ball Electroscope. This is a convenient little instrument for ascertaining practically whether a body is electrified or not. It consists (fig. 3) of a small ball of elder-pith (which is very light) hung on a stand by a fine silk thread. To test a body we simply hold it near the pith ball and observe whether the latter moves towards it; if it does the body is electrified, if not it is neutral. Care must of course be taken that to begin with the pith ball is neutral, otherwise, for the reason in § 3, the experiment will be misleading. Should the ball have become electrified by accident, or as the result of some previous experiment, it may be rendered neutral by gently squeezing in the fingers (§ 15). The process of rendering an electrified body neutral is termed *de-electrifying* or *discharging*.

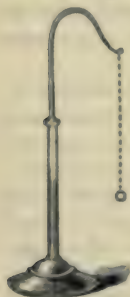


Fig. 3.

7. Can All Substances be Electrified? This is one of the questions Dr. Gilbert set himself to answer, and the pith-ball electroscope enables us to do so for ourselves. We find by experiment that any of the substances mentioned in list 1 (see below), if held in the hand and rubbed with almost any soft material, will afterwards attract the pith ball, and is therefore electrified.

But if we treat any of those in list 2 *in the same way* it will not affect the pith ball, and is therefore not electrified.

List 1.

Amber.
Sealing-wax.
Resin.
Sulphur.
Gutta-percha.
India-rubber.
Glass.
Ebonite.

List 2.

ANY METAL, e.g. iron, copper, brass, etc.
Ordinary wood.
Bricks, stones, etc.
Paper under ordinary circumstances.
Vegetable tissue.
Animal tissue.

Now, what this shows is that if we take any of the things in list 2, and *hold them in the hand and rub them*, they do not in this way become electrified; that is a very different thing from saying that we cannot electrify them *by any means whatever*.

8. Insulators and Conductors. Look at fig. 4. A is an ebonite rod with a socket D D, and C is an iron rod with an end put in the socket and held fast by the screw B. If now A be held in the hand (taking care not to touch B or C), and C be gently beaten with a dry rubber and then held near the ball of the pith-ball electroscope, it will attract it strongly. By this means we have therefore *electrified the iron rod*, and we can electrify any of the substances in the second list of § 7 in the same way, the essential point being that they must not be held directly in the hand, but must be *mounted on a handle made of one of the substances in the first list*, the best being ebonite. Dr. Gilbert did not know this: he thought that none of the things in the second list could be electrified, so he called them *non-electrics* while those in the first list he called *electrics*; but nobody uses these terms nowadays, because they convey quite wrong ideas. The things in the first list are now called *insulators*, and those in the second *conductors*. We shall learn in § 11 *why* these terms are used; just now we will regard them as mere names.



Fig. 4.

9. Discharging a Conductor. If in fig. 4, after rubbing the rod and satisfying ourselves by the pith ball that it is electrified, we touch it with the finger and again try it with the pith ball, we shall find that it will no longer affect it; we thus learn that touching a freely electrified conductor reduces it to a neutral state, *i.e.* (§ 6) *de-electrifies* or *discharges* it. The same effect is produced by causing the electrified conductor to come into contact with the walls of the room or the floor. If a metal or wooden rod be stuck in the floor and an electrified conductor allowed to touch the top of it, the conductor will be at once discharged, but if the rod be of glass or ebonite or gutta-percha it will remain electrified.

10. General Conclusion. Now, remembering that metals, wood, stone, human flesh, etc., are what we have termed conductors, while glass, ebonite, etc., are what we have termed insulators, and looking at all the experiments in §§ 8 and 9, what we learn is that *a conductor can be freely electrified when and only when an insulator is interposed between it and the earth, and also that after a conductor has been thus electrified it becomes discharged by making a conducting path from it to the earth.*

When an insulator is interposed between a conductor and the earth the conductor is said to be *insulated*, while, when there is a conducting path all the way, it is said to be *earthed*. Thus *we can freely electrify an insulated conductor but not an earthed one, while earthing a freely electrified conductor at once discharges it.*

11. Explanation of Difference. An electrified conductor remains electrified while insulated, but becomes at once de-electrified when earthed. And the most natural explanation *so far* is that the electrification is due to *something which can flow along conductors but not along insulators*; to this "something" we give the name *Electricity* (cf. § 26). When the electrified conductor is earthed this electricity flows along the conducting path into the earth and is lost to *us*, though it by no means follows that it is *really* lost, while when insulated the electricity remains on the conductor. And now we see why the terms "conductor" and "insulator" are used: a conductor is a substance which allows electricity to flow along it, that is, *conducts* it; while an insulator or non-conductor is one which does not do so, but blocks the way against its passage and so keeps it in its original place.

It is clear now why we cannot electrify a conductor all the while it is held in the hand: the human body is a conductor and cannot block the way, so that the electricity cannot remain on the conductor. Of course, with a non-conductor the electricity cannot flow along it, so that it serves as its own insulator. Incidentally we learn too that the main body of the earth is a good conductor, otherwise, of course, the electricity could not so readily pass into it.

Conductors may be roughly compared to water pipes, and insulators to taps *turned off*. The tap blocks the flow of the water, and the insulator blocks the flow of electricity. Turning on the tap corresponds to earthing the conductor.

12. Part played by Air and Moisture. Dry air is an excellent insulator, so that when a conductor is on an ebonite stand it is insulated from the earth all round; if the air were a conductor, the ebonite stand would, of course, be useless.

Unfortunately *water* is a conductor, and anything, even ebonite, loses its insulating power if wet. None of the substances in list 1, § 7, can be electrified by holding in the hand and rubbing if they be damp themselves, or if the rubber be damp. For numerous electrical experiments, we require electrified conductors, and it is best to have a supply of metal balls, rods, etc., mounted on ebonite supports. Not unfrequently glass supports are employed; but they are not nearly so good, because the moisture of the air sticks very persistently to the surface of the glass, which it does not do to ebonite; the evil may be to some extent remedied by coating the glass with a layer of shellac varnish. Silk is a good insulator, hence sometimes metal balls are hung up by silk threads: unspun silk answers best,—it absorbs very little moisture.

It should be observed that *moist air* itself is an insulator, for it is merely air containing the *vapour* of water, and this possesses very little if any conducting power; it is only water in the liquid form that is a good conductor. And when electrified bodies lose their charge by exposure to damp air it is because such air deposits a thin layer of *liquid* moisture on the insulating supports and so renders *them* conductors.

13. Classification of Conductors and Insulators. The conducting and insulating power of different substances varies greatly, and, indeed, one cannot draw a sharp line between conductors and non-conductors; some substances, such as wood and paper, can hardly be called the one or the other. It is usual to give some such classification as the following, it being understood that the "good insulators" must be dry, as otherwise they cease to be such.

Bad Insulators.	<div style="display: inline-block; vertical-align: middle;"> <div style="display: inline-block; vertical-align: middle;"> Silver. Copper. Other metals. Gas coke. Charcoal. Graphite. Acids. Metallic salts. Water. The Body. </div> </div>	Good Conductors.
-----------------	---	------------------

Partial Insulators.	{ Linen. Cotton. Wood. Stone. Marble. Paper. Ivory. }	Partial Conductors.
Good Insulators.	{ Oils. Porcelain. Wool. Silk. Resin. Sulphur. Gutta-percha. Shellac. Sealing-wax. Ebonite. Paraffin-wax. Glass. Air. Vapour of Water. }	Bad Conductors.

14. Distribution of Electrification. If what we have said in § 11 as to *flow* be true, we should expect that if we took a metal rod (mounted on an insulating handle) and rubbed one end, the electrification would distribute itself all over the rod, whereas with an ebonite or glass rod we should expect it would remain at the end rubbed. Experiment tells us that this is the case, for if in fig. 4 we rub the top of the iron rod all parts of it will attract the pith ball, while if we rub the top of an ebonite rod it is only the top that will attract. Thus *an electrification distributes itself all over a conductor*, but not over an insulator unless, of course, the whole insulator be rubbed.

A word of caution is needful here: we say an electrification distributes itself all *over* a conductor, not all *through* it. We shall learn later that the electrification on a conductor is always *all on the surface*,—it does not penetrate the interior at all; whereas, curiously enough, in non-conductors it *does* penetrate the interior to some extent (§ 64).

15. Transference of Electrification; Electrification by Contact. The view set forth in § 14 leads to another important point. Suppose we have two conductors (say two brass balls), each mounted on an ebonite support as in fig. 5, and either touching each other as shown

in the diagram, or placed some distance apart and connected by a copper wire. Then they are in conducting or "electrical" communication, and, indeed, from an electrical point of view are *all one conductor*. Hence, if we electrify A, the electrification will distribute itself over *the entire surface*, and both A and B will be electrified. This can easily be proved by separating them and afterwards testing each separately with the pith-ball electroscope, when each will be found to attract the ball.

Again, suppose that to begin with the balls do not touch and there is no wire, or, to put it technically, they are insulated not only from the earth but from one another, and that we now electrify A and afterwards put it into conducting communication with B (care of course being taken not to earth either A or B). Then B acquires *some* of A's electrification, while some is retained by A, which can all be proved by the pith-ball electroscope. This way of electrifying B is called *electrifying by contact*, and the electrification B acquires is called *contact electrification*: it is manifestly due to part of the electricity which existed on A flowing on to B, the rest remaining on A.

There is no difference between a contact electrification and one obtained by direct friction, except as respects the way of giving it; but it should be noticed that, since electricity will not flow over non-conductors, we must, if we wish effectually to electrify them, employ direct friction: we cannot impart any considerable charge to or take such from them by contact. If we touch an insulated metal ball with an electrified ebonite rod, the ball will receive a certain electrification, but only from those points of the rod which the ball has actually touched, so that the electrification acquired will be small. In like manner, if an electrified ebonite rod be touched by the finger it will be de-electrified at the place touched but nowhere else; in order to de-electrify it completely it must be squeezed in the hands along its entire length. Elder-pith is not a very good conductor, and hence it is (§ 6) that in discharging the pith-ball we must squeeze it all over.

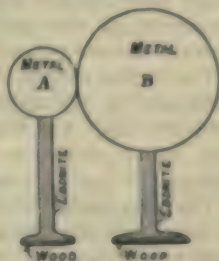


Fig. 5.

By the contact method we can electrify substances such as water when direct friction is out of the question. If a small glass of water be placed on an insulating stool,* and an electrified conductor be made to touch the surface of the water, the latter will become electrified, as can easily be proved by the pith-ball electroscope provided the electrification be pretty strong.

The contact method is very useful when we wish to electrify some conductor or arrangement of conductors which we cannot conveniently rub. For this purpose we merely take an insulated metal ball, rub it, and then touch the conductors with it, repeating the process until we have as strong an electrification as is desired.

The same method is also convenient for examining the electrification of any conductor which cannot readily be moved so as to bring it near an electroscope: in this case we take a small insulated ball, allow it to touch the conductor, and then carry the ball to the electroscope. Sometimes a *proof-plane* is used for this purpose; it is simply a small flat circular piece of brass, about as big as a shilling, mounted on an insulating handle. This instrument has also more elaborate uses, as will be explained in § 65.

QUESTION :—What will happen if we touch (1) an electrified brass ball with a dry glass rod, (2) an electrified ebonite rod with an insulated carrot, (3) an electrified stick of sealing-wax with a piece of dry india-rubber tube, (4) an electrified ebonite rod with a wisp of damp silk?

16. Electrical Repulsion. We have seen that if we hold an electrified body near the pith-ball electroscope the ball will be attracted. But we cannot work with this instrument without discovering something else, viz., this:—The ball is attracted, and if it be allowed to touch the electrified body is afterwards driven away from it or *repelled*; and sometimes the repulsion is so strong that it is impossible to make the electrified body approach within several inches of the ball. Now, why is this? Well, in the first place we know that when the ball touches the rod it receives a contact electrification, and as the ball is suspended by a silk thread which is an insulator this electrification must remain on the ball. So that

* An insulating stool or stand is a very small table mounted on glass or ebonite legs, ebonite being preferable.

it seems pretty clear that the repulsion must be caused by the electrification of the ball. And an additional experiment renders this an absolute certainty, for we have only to discharge the ball when it again becomes *attracted*. We thus learn that an electrified body may, at any rate under some circumstances, *repel* another electrified body.

QUESTION:—If the pith ball were gilt and suspended from a brass stand by a very fine copper wire instead of a silk thread, would there be any repulsion?

17. Further Study of Attraction and Repulsion. Now, in fig. 1 or 2 let the rod represent one of *glass which has been rubbed with silk*. Take another rod of glass, rub it with silk and hold it near the one on the pivot (or stirrup): the latter will be *repelled*. Here, then, we have a more direct instance of one electrified body repelling another.

Now put the glass rods aside. Take an *ebonite rod rubbed with fur* and set it on the pivot, then take another ebonite rod, rub it with fur and hold it near the one on the pivot: the latter will be *repelled*. Here is another case of the same sort.

Lastly, set on the pivot one of the glass rods rubbed with silk, and hold near it one of the ebonite rods rubbed with fur: the glass rod will be *attracted*. Or set on the pivot one of the ebonite rods rubbed with fur, and hold near it one of the glass rods rubbed with silk: the ebonite rod will be *attracted*. Here we have instances of one electrified body *attracting* another electrified body.

These actions are extremely important, and may be summarised thus:

- Two glass rods rubbed with silk *repel* one another,
- Two ebonite rods rubbed with fur *repel* one another,
- A glass rod rubbed with silk and an ebonite rod rubbed with fur *attract* one another.

18. Two Kinds of Electrification. Now let us follow up these experiments and see what we can learn from them. Consider a glass rod rubbed with silk, and call it A. Then a glass rod rubbed with silk *repels* A, while an ebonite rod rubbed with fur *attracts* A. Since, then, the glass rod rubbed with silk and the ebonite rod

rubbed with fur behave differently towards one and the same thing. A, they must be in *different electrical conditions*; in other words, the electrifications on them are in some way different, though in *what* way we cannot so far tell. Further, since a pair of glass rods rubbed with silk repel each other, and a pair of ebonite rods rubbed with fur do the same, while one glass rod rubbed with silk and one ebonite rod rubbed with fur attract each other, we learn that bodies in *similar* or *like* electrical states *repel*, and bodies in *dissimilar* or *unlike* electrical states *attract*.

The experiments therefore teach us two things, viz.—

(1) *There are two different kinds of electrification.*

(2) *Bodies possessing like electrifications repel, those possessing unlike electrifications attract.*

We must be very careful to note that the experiments teach us *no more than this*; we have no right to infer that there are two kinds of *electricity*—all we can say is that there are two ways in which the electricity can manifest itself.

We can now explain why the pith ball is repelled after touching the electrified rod: it is because it receives by contact an electrification of the *same kind* as the rod. But this only carries us one step, for *why* two similarly electrified bodies repel or two dissimilarly electrified bodies attract nobody knows.

The second of the above propositions is frequently enunciated thus:—*Like electrifications (or charges) repel, unlike attract.*

The kind of electrification that exists on a glass rod rubbed with silk is termed a *positive electrification* or a *positive charge*, that on an ebonite rod rubbed with fur a *negative electrification* or *negative charge*. We shall see in § 26 that these terms are very appropriate; for the present we regard them as mere names. The expressions *positive electricity* and *negative electricity* were frequently used by the older writers, and are still sometimes met with; but it is best to avoid their use, as they seem to commit us to the notion that there are two kinds of *electricity*.

EXERCISE:—A pith-ball suspended by a silk thread is touched by a negatively charged ebonite rod; the latter is then taken away and a positively charged glass rod held near the ball: state and explain what will happen.

19. Further Study of the Electrified Rods. If we take a positively charged glass rod, balance it on a pivot and hold near it a negatively charged ebonite rod, it will be *attracted*. But now, instead of the ebonite rod, let us take a neutral body; then on holding it near the glass rod, the latter will again be *attracted*. Hence, if we hold near the glass rod a body whose electrical condition we do not know, and find that it is *attracted*, we are left in doubt as to whether the body was originally negatively electrified or neutral. There is nothing surprising in this when we remember that the inductive action (§ 5) of the glass rod modifies the state of the body, so that what it does *when it is near the rod* is no sure test of its state *when it is away from it*. But there is a still more striking instance of this. If we take two glass rods, one very strongly and the other very feebly electrified by rubbing with silk, place one on a pivot and hold the other near it, we shall find that they attract! Now, this looks like a flat contradiction of the law that similarly electrified bodies repel; but here again we must remember that we have inductive action: the feebly electrified rod is, before the other is brought near, nearly neutral, and the influence of the stronger one so much modifies its state as actually to overcome the effect of its original electrification. So that whenever a positively electrified body attracts one which *before it was brought near* was either neutral or positively electrified, it is because the very fact of bringing it near utterly alters its original condition, in other words *the very test applied alters the character of the thing to be tested*. There is therefore no contradiction. Of course, all these remarks apply, *mutatis mutandis*, to negatively electrified rods. And they lead to a very obvious practical conclusion: viz., that the mere attraction of a body by one having known electrification gives us *no reliable information* as to the electrical state of the body we are examining, or, as it is generally expressed, *attraction is no test of electrification*.

But suppose we set on the pivot our glass rod which has been rubbed with silk (and is therefore positively electrified), hold near it a body whose electrical state we do not know, and find that it is *repelled*. What does *that* tell us? Well, the body under examination clearly cannot before it was brought near the rod have been negatively electrified, for then it would be attracted. Neither can it have been neutral, for then it would also have been attracted. *Therefore it must have been positively electrified*. Similarly if it had repelled

an ebonite rod rubbed with fur it must have been negatively electrified. Here, then, we have a sure and certain test: *the repulsion of a body by an electrified rod shows that the body originally possessed the same kind of electrification as the rod.*

20. How to Test a Body. Practically the condition of a body may be tested as follows:—We take a positively electrified glass rod on one pivot, a negatively electrified ebonite one on another pivot, and a neutral pith-ball electroscope; these three being placed some distance apart to prevent any appreciable inductive action. We then take the body under examination—*e.g.*, an insulated metal ball—and bring it near the pith ball: if the latter does not move, the body is neutral, and we need go no farther. But if the pith ball moves the body is electrified, and we then use the rods to find out the *kind* of electrification: we try first one rod and then the other. The body can never *repel both*: what usually happens is that it repels *one*, and we then know that its electrification is of the same kind as that of the rod repelled. If it should *attract both*, which does not often occur, we know its electrification is weak, but are left in doubt as to its kind; it is in that case sometimes recommended to bring the body gradually up to first one rod and then the other from a distance, so as to try and catch the repulsive effect before the inductive action becomes strong enough to overcome it, but in practice this does not work very well. Sometimes, in place of the rods, two pith-ball electroscopes are employed of which the balls have been electrified by contact, one positively and the other negatively. But in neither case is the method so delicate as could sometimes be wished, and it is better to use the gold-leaf electroscope as explained in § 29.

21. Electrification of Sundry Bodies. Suppose we now take any body at random, and rub it with any rubber at random, we can by § 20 find out the kind of electrification it acquires. We should thus find such results as these:—

Sealing-wax rubbed with flannel becomes negatively electrified.

Wood	"	"	"	"	"	"
Paper	"	"	fur	"	"	"
Glass	"	"	"	"	"	"
Resin	"	"	cloth	"	"	"
Paper	"	"	india-rubber	becomes positively electrified.		
An apple	"	"	gun-cotton	"	"	"

We shall also find that a piece of *rough* or "*ground*" glass rubbed with silk becomes negatively electrified. When we speak of a "*glass rod*" we always mean ordinary smooth glass unless the contrary is stated. A kind of rubber sometimes used is made by smearing a piece of silk with a paste consisting of tin foil, mercury and resin-ointment ground up together; this paste is called *electric-amalgam*, and a rubber thus prepared is called *amalgamated silk*. Almost anything, even ebonite, when rubbed with this becomes *positively* electrified; and almost anything, even glass, when rubbed with fur becomes negatively electrified.

It is clear from all this that the kind of electrification acquired by a body depends not only upon the body itself, but also upon the rubber.

22. How to Electrify a Conductor. The following case is of great practical importance:—*Any common metal (such as iron, brass, copper, etc.) becomes positively electrified when rubbed with india-rubber, and negatively when rubbed with fur.* We thus have a practical method of electrifying our metal balls, rods, etc., either positively or negatively. The best way is to hold the fur or a sheet of thin india-rubber in the left hand, and with the right beat the metal sharply against it, taking care, of course, not to earth it by allowing it to touch the fingers. One stroke against the fur or three against the india-rubber are generally enough to produce a fair electrification. If the conductor to be electrified be not conveniently movable, we may electrify one of our balls in this way, and transfer the electrification to it by contact (§ 15).

QUESTIONS:—1. An iron rod (mounted on an ebonite handle) is beaten with india-rubber and held near an ebonite rod which has been rubbed with amalgamated silk and which is balanced on a pivot. What will happen?*

2. A negatively electrified ebonite rod is balanced on a pivot, and a neutral brass ball placed near it: what happens?

* In all questions of this kind it is intended that the natural action of each electrified body is strong enough to have, so to speak, its own way, and not to be overcome by induction.

23. Both Kinds of Electrification produced at the Same Time.

Take a piece of fur, A (a camel-hair brush is more convenient), and mount it on an ebonite handle, and also take a neutral ebonite rod, B. Have ready a positively and a negatively electrified rod, each balanced on a pivot. Rub one end of the ebonite rod B with the insulated brush A, and afterwards separate them. Hold B near the negative rod on the pivot: it will be repelled, showing that it is negatively charged, as we already knew. Then hold the brush A near the positive rod: it will be repelled, showing that *the brush is positively charged*.

Thus the ebonite and the brush, when rubbed together, both acquire electrification, but of opposite kinds. Now, the same thing happens in every case, as can be shown by similar experiments, using other substances and other rubbers. The only reason for insulating the rubber is because most rubbers belong to the class of partial conductors (§ 13), so that unless insulated most of their electrification passes into the earth and it is difficult to detect it. It should be noted, too, that whenever two *exactly similar* substances are rubbed together, neither of them, as a rule, becomes electrified. The conclusion may therefore be stated thus:—*Whenever by rubbing together two bodies one of them becomes electrified, the other always becomes electrified at the same time but in the opposite way.*

EXERCISES:—1. A piece of india-rubber (which is a good insulator) is used to beat an iron rod, and is then held near a pivoted glass rod that has been rubbed with silk. State and explain what happens.

2. A brass rod is balanced on a needle point which is mounted on an ebonite support, and is stroked with a camel-hair brush. After this the brush is first de-electrified, then insulated, brushed over a dry glass bottle, and held near the brass rod. State and explain what happens.

24. Frictional Order. Now look at this list:—

- | | |
|--------------------------------|------------------------------|
| 1. Fur. | 11. Glass (rough). |
| 2. Wool (flannel, cloth, etc.) | 12. The hand. |
| 3. Wood. | 13. Common metals. |
| 4. Shellac. | 14. India-rubber. |
| 5. Resin. | 15. Amber. |
| 6. Sealing-wax. | 16. Sulphur. |
| 7. Glass (smooth). | 17. Ebonite. |
| 8. Cotton. | 18. Gutta-percha. |
| 9. Paper. | 19. Silk (amalgamated). |
| 10. Silk (plain). | 20. Gun-cotton or Collodion. |

These substances are arranged in what is sometimes called *frictional order*; and the point is that if any two of them be rubbed together, the one *highest* in the list becomes electrified *positively*, and the one *lowest* *negatively*.

It should be noticed, however, that in some cases the results are rather uncertain, on account of variations in different specimens of the materials. But there is no uncertainty about the standard cases of glass rubbed with silk, ebonite with fur, and metal with fur and with india-rubber.

25. The Two Electrifications Neutralise Each Other. We must now resume the consideration of § 23, and we will begin by adding a fresh experiment. Take the mounted brush A and the ebonite rod B, and see that everything to begin with is neutral. Hold the ebonite rod by one end and rub the other with the brush, but *do not separate them*. Bring them both together near the pith-ball electroscope: there will be *no* movement. Now, we know by § 23 that the ebonite is negatively and the brush positively electrified; this new experiment, therefore, tells us that *the two electrifications neutralise one another*, in other words, the ebonite and brush taken as a whole are *not electrified*, they are *neutral*.

A like result is observed in all cases. If we rub an insulated brass ball with an insulated brush, the two together will not affect the electroscope, though either separately will do so. (See also § 55.)

EXERCISE:—An ebonite rod is supplied with a flannel cap about an inch long, which fits over one end. Round the flannel is wound a piece of strong silk thread, with about four inches hanging loose. A person holds the rod in his left hand and the loose end of the silk in his right, and turns the flannel cap several times round. The rod with the cap on it is then held near the pith-ball electroscope: what will happen? The flannel cap is then taken off (the silk thread only being touched), and it alone held near: what will happen? The cap is then squeezed in the fingers, again put on the rubbed end of the rod and the two held near: what will now happen?

26. Electricity. One-Fluid Theory. We have now sufficient experimental evidence to enable us to form *some* idea of the nature of electricity and of what happens to it when bodies are electrified. The evidence in question consists of these three facts:—

1. There are two kinds of electrification.
2. When one is produced (by friction) the other is produced at the same time.
3. They are produced in such a way as when taken together to neutralise one another.

To this may be added that whenever two electrifications of the same kind are given to the same body they increase each other's effects, whereas when two of different kinds are given they always neutralise each other, at any rate *partly*. This is a minor point. It may, however, be noticed that the fact that the two electrifications always tend to neutralise one another is sufficient to justify the terms *positive* and *negative*: if we place a positive electrification on a body and then a negative one, the latter act is equivalent to subtracting more or less of the positive one; hence the terms positive and negative have the same kind of meaning as the sign + and - in algebra.

But now to our main point. What is at any rate one reasonable way of regarding two things which can neutralise each other? It is to look upon one as caused by an *excess* of something, and the other by a *deficit* of that same something. Let us then picture to ourselves every body in its ordinary or neutral state as containing a stock amount of something, and let us call that something *electricity* (cf. § 11). Let us further picture a freely and positively electrified body as containing *more* than its stock amount—*i.e.*, as *excess* of electricity; and a freely and negatively electrified one as containing *less* than its stock amount—*i.e.*, a *deficit* of electricity. Then we shall have a reasonable view of things, and one that will carry us a long way in the explanation of facts.

At the outset this view enables us to assign a distinct meaning to the term *charge*. By a *positive charge* is to be understood the excess of electricity on a body over and above its stock amount, and by a *negative charge* the deficit of electricity on a body below its stock amount. Thus *electrification* and *charge* do not convey exactly the same idea: the former is a mere name for the condition of an electrified body, while the latter is that to which this condition is due. And to guard against future mistakes it should be noticed that it is only *free* electrifications which can properly be regarded in this way, for, as will be seen in § 49, a body under inductive influence may exhibit electrification simply as the result of some of its electricity being displaced from one part of it to another.

In § 11 we saw that electricity could flow through conductors. And because it can thus flow it is called a *fluid*. Beyond that we know next to nothing about it: it resembles no known material fluid, such as water or air. Most probably it is some form of the *ether* which fills all space and is mixed up with all matter. It has

no weight, and we cannot get hold of it so as to measure it by the cubic inch or pint. We can only study its effects and measure its amount indirectly therefrom. Moreover, we have no knowledge of the *actual amount* of electricity in any body; all we can deal with is *excesses or deficits*, i.e., *charges*.

The ideas herein set forth constitute what is known as the *one-fluid theory* of electricity. It was originally propounded by Benjamin Franklin about the middle of the eighteenth century.

27. Previous Experiments viewed in the light of the One-Fluid Theory. The fundamental facts of electrical attraction and repulsion have not yet been explained either by the one-fluid or any other theory. But apart from this, several other facts which we have learned can be readily accounted for.

Consider for example the following cases:—

1. Take a positively electrified conductor; it contains an excess of electricity which constitutes its positive charge. Now earth it, *the excess escapes to earth* (cf. § 9).

2. Take a negatively electrified conductor; it contains a deficit of electricity which constitutes its negative charge. Now earth it, then *electricity runs into it from the earth*, making good the deficit (cf. § 9).

REMARKS.—We must regard the earth as a vast storehouse of electricity; whenever an electrified conductor is earthed, a small quantity of electricity is imparted to or taken from the earth, but on account of the enormous size of the earth compared with that of any of our conductors, this makes no appreciable difference in the earth's stock.

When electricity passes from a body to the earth this is properly expressed by saying a positive charge passes to earth; and when electricity passes *from the earth to a body*, as in Case 2 above, this is conveniently expressed by saying a *negative charge passes to earth*.

QUESTION:—Explain electrification by contact according to the one-fluid theory.

3. Beat an insulated metal ball with india-rubber. Each to begin with contains its stock amount of electricity. The result of the beating is to transfer some of the electricity out of the india-rubber into the ball, so that the latter acquires a positive charge and the

former a negative. And whenever we rub two things together any electricity imparted to one must be taken from the other, hence the two electrifications always appear together, one on the body rubbed and the other on the rubber. Moreover, *the amount taken from one must be equal to that given to the other*: in the two together there is neither excess nor deficit (cf. § 25).

28. Dielectric—Electric Field. Consider an electrified body, A, surrounded by air, and let a body, B, be placed near it without touching; then B experiences a force which may be attractive or repulsive according to circumstances. In the early days of the science it was customary to regard this force as, so to speak, jumping from A to B with nothing to help it; but modern investigations have shown this view to be wrong, and that *the air plays an important part in the transmission of the force*, though in what way it acts we do not exactly know. If between A and B we put a plate of unelectrified glass, paraffin-wax, ebonite, or any other insulator, B still experiences the attractive or repulsive force, although the magnitude of the force is more or less altered. Thus *all insulators are capable of transmitting electrical force*. And as we shall learn later, it is not only *force*, i.e., mechanical attraction or repulsion, which they can transmit, but the influence termed electrical pressure or potential (Chap. II.).

When an insulator is regarded as a medium for the transmission of any kind of electrical influence, it is termed a *dielectric*; thus a dielectric is the same thing as an insulator, but the two names refer to different properties of it. The word *insulator* denotes that it *does not allow electricity to flow over or through it*; the word *dielectric* that it *does allow electrical influence to be transmitted across it, and itself plays an actual part in conveying that influence*.

The whole region round about an electrified body or set of such is called an *electric field*. The strength or “intensity” of the field in general decreases rapidly as we recede from the electrified bodies, and in ordinary cases becomes practically inappreciable at a distance of one or two feet.

EXERCISE:—An electrified brass ball is placed in a dry unelectrified glass tube and held near a neutral pith-ball suspended by a silk thread; how will the pith-ball behave?

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER I.

1. Distinction between *Electrification* and *Electricity* (§§ 4, 18).
2. Distinction between *Free* and *Induced* Electrification (§ 5).
3. Distinction between *Conductors* and *Insulators* (§ 8).
4. The charge on a conductor does not penetrate into its material (§ 14).
5. Law of attraction and repulsion—viz., *Like electrifications repel, unlike attract* (§ 18).
6. Mode of electrifying conductors practically—viz., by beating with india-rubber for positive, and with fur for negative (§ 22).
7. Simultaneous production of the two kinds, so as to neutralise each other (§§ 23, 25).
8. *The One-fluid Theory.* Every body in a neutral state contains a stock amount of electricity. A positive charge is an excess of electricity, and a negative a deficit. Exact significance of the term *charge* as distinguished from *electrification*. What we *do* and what we *do not* mean by speaking of electricity as a "fluid."
9. The earth a vast storehouse of electricity. What happens when we earth a freely-charged conductor (1) if positive, (2) if negative. Explanation by the one-fluid theory of electrification by contact and by friction (§ 27).
10. A *dielectric* permits of *electrical influence* being transmitted across it, but not of *electricity flowing through it* (§ 28).

EXERCISES ON CHAPTER I.

1. When a piece of sealing-wax and a piece of dry flannel are rubbed together one becomes positively and the other negatively electrified. When a piece of dry paper and a piece of india-rubber are rubbed together one becomes positively and the other negatively electrified. How could you find out which of the four things, sealing-wax, flannel, paper, india-rubber, are in the same electrical state?
2. Arrange the following substances in the order of their conducting powers for electricity, putting the name of the best conductor first:—air, copper, glass, iron, water, wood, fur, silk.

3. A pith ball is suspended from a metal stand by a fine thread. If you have a strongly electrified glass rod, how can you find out whether the thread is a conductor or non-conductor of electricity?

4. State the disadvantages of glass as an insulator, and describe the best means of overcoming them.

5. Two pairs of light pith balls are hung at the opposite ends of an insulated conductor, one pair being suspended by silk and the other by cotton threads. Describe and explain the behaviour of the balls if the conductor is gradually electrified more and more strongly.

6. State clearly the evidence for the opinion that there are two kinds of electrification.

7. Write a short essay on the one-fluid theory of electricity, and explain in accordance therewith (1) the positive, (2) the negative electrification of a conductor by contact. Explain also the discharge of (1) a positively, (2) a negatively electrified conductor.

CHAPTER II.

POTENTIAL.

29 Preliminary Considerations: Pressure of the Air. It is a matter of common knowledge that the air exerts pressure. In an ordinary room or out of doors this pressure amounts to about 15lb. weight on every square inch of surface, but varies slightly with changes of the weather. In a confined space such a corked bottle the pressure may vary much more and depends among other things upon the quantity of air contained in the space.

Any instrument for indicating the pressure of the air is called a *pressure gauge*. Fig. 6 shows a simple form; it consists of a glass tube, A P Q S R B, bent into the shape shown and containing a quantity of mercury, H Q S K. The ends A and B are open, and when the gauge is simply exposed to the air in the room the mercury in both limbs experiences the same pressure and it stands in both at the same level, H K. It will also stand at the same level if the open ends, A, B, be connected to two different vessels at *equal pressures*. But if the pressure in the one attached to A be greater than in the other, the mercury in P Q will be forced down and that in S K up, so that it will stand at different levels, H', K', and the greater the pressure difference in the two vessels the greater will be the difference of levels.

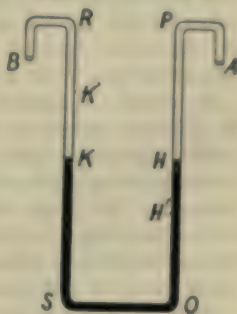


Fig. 6.

30. Study of an India-rubber Air-bag. Now let us more expressly consider the following case. Take an india-rubber bag (fig. 7) full of air and provided with a stop-cock. Turn the cock on, taking

care not to press the bag, then maybe air will flow out or in according to circumstances. When all flow has ceased the bag possesses a

certain definite quantity of air, which we will call its "stock amount." We will also speak of the bag under these circumstances as being "neutral." If in any subsequent experiment we cause the bag to receive *more* than its stock amount



Fig. 7.

of air we will call the excess a "positive charge," if *less* we will call the deficit a "negative charge."

Now take a pressure gauge and attach the "neutral" bag to it, the mercury will stand at the same level in both limbs showing that *the pressure of the air in the bag is the same as in the room outside.*

Next give the bag a "positive charge" by forcing a little more air into it and again attach the gauge, the pressure of the air in the bag will be found *greater* than in the room.

Lastly give the bag a "negative charge" by sucking a little air out, and again test by the gauge, when the pressure in the bag will be found *less* than in the room.

Now take *two* bags of any sizes equal or unequal and charge them to *different pressures*. Connect their nozzles by a piece of india-rubber tube, and open the cocks. Then air will be found to flow *from the one of higher to the one of lower pressure*, and on afterwards testing by the gauge *each will be found to be at the same pressure*. If the two bags to begin with are at the same pressure then on connecting them no flow occurs either way and the pressure remains unchanged—in short *nothing whatever happens*.

In the case of a bag a small change in the quantity of air in it may materially alter its pressure. But in the room outside we cannot by any artificial means produce alterations of pressure because the air in it is in communication through doors, chimneys, window-chinks, etc., with the vast mass of air outside and such small quantities as we can add to or take from it can have no effect; such alterations can only come about slowly as the result of weather changes, and therefore during any experiments we may make with our bags the pressure in the room remains *constant*—equal in fact to the

atmospheric pressure at the time of the experiment. Suppose now that instead of *two* bags we take only one and turn on the cock so as to open up communication between the air in it and in the room, then just as in our previous experiments air will flow from or into the bag according as the pressure in the latter was above or below the atmospheric pressure.

31. Study of a Charged Conductor, Electrical Pressure or Potential. We have seen (§ 11) that in a conductor electricity flows readily—it behaves like a fluid, while in insulators it does not flow—it behaves like a solid. Comparing then the conductor and the air-bag, we shall regard the electricity in the conductor as corresponding to the air in the bag and the electricity in the surrounding dielectric (generally the air in the room) as corresponding to the india-rubber; the electricity in the earth corresponds to the air in the room outside the bag. Making two conductors touch, or connecting them by an insulated metal wire corresponds to joining the nozzles of two bags and then turning the cocks, while earthing a conductor corresponds to simply turning on the cock of a bag so as to open up communication between the air in it and in the room outside.

We are now in a position to introduce what is perhaps the most important conception in the whole range of electrical science. We know that air exerts pressure, and it is conceived that electricity exerts an influence bearing the same relation to it that pressure does to air—this influence is called *Electrical Pressure* or more commonly **POTENTIAL**.

It is found that this conception is of the greatest possible service in explaining electrical phenomena; it is, however, advisable at the outset to guard against a possible misconception. Air, water, india-rubber, etc., are all forms of *matter*, and the pressure which they exert or is exerted on them is something with whose nature every one is familiar—it is simply a mechanical force like a pull or a push. But electricity is *not matter*, and what the nature of electrical pressure may be is not known; all we can say is that just as mechanical pressure tends to move matter, so electrical pressure or potential is an influence which tends to move electricity.

When we pump excess of air into a “neutral” air-bag we increase its pressure, while if we suck some of the air out we diminish it. In

like manner when we give a conductor a positive charge we must picture its potential as being increased, and when a negative charge as diminished.

If we open the cock of a "neutral" air-bag nothing happens, the reason being that the original pressure of the air in the bag was the same as in the room. Again if we earth a neutral conductor nothing happens, and as we shall more fully see in the next article this is because the potential of all neutral conductors is equal to that of the earth. Now in § 30 we have seen that the pressure of the air in the room is constant during any experiment we may make, and in like manner on account of the enormous size of the earth compared with our apparatus the small quantities of electricity which we impart to it or take from it cannot affect its electrical pressure; *we may therefore regard the potential of the earth as constant throughout our experiments.* This constant value is said to be zero; now the literal meaning of "zero" is "nothing," but it is not meant that the earth has no electrical pressure, all that is intended is that the potential of the earth is *our standard of reference* just as on the Centigrade thermometer we speak of the temperature of melting ice as zero. Moreover, just as temperatures are regarded as positive or negative according as they are above or below this temperature, so are potentials regarded as positive or negative according as they are above or below the potential of the earth.

It appears therefore from what has before been said that positively charged bodies have positive potential, negatively charged ones, negative potential, and uncharged ones zero potential; it is, however, very important to note that in the present discussion we are for simplicity confining our attention to bodies *not under inductive influence* (§ 5): we shall subsequently learn that *these statements are not true when inductive influence comes into play* (§§ 41-43).

32. Poisson's Principle. In § 30 we have seen that if two air-bags at different pressures be connected, air flows from the one of higher to the one of lower pressure until the pressures are equalised, while if the pressure to begin with were the same, nothing happens.

Now if we put two conductors into electrical connexion (either by allowing them to touch or joining them by an insulated wire), it is found that a flow of electricity may or may not take place between them according to circumstances, and the question is *what determines*

the flow. The answer was first given by Poisson in the following theorem, which is precisely analogous to the one for air-bags above mentioned:—*If two conductors at different potentials be put into electrical communication, electricity will flow from the one of higher to the one of lower potential until their potentials become equal, while if their potentials were equal to begin with, then on connecting them nothing whatever happens.* This is known as *Poisson's Principle*; it is the fundamental principle of Electrostatics, and we shall have constant occasion to refer to it in subsequent articles. More briefly it may be stated thus:—*The potential at all parts of a conductor or of any number of conductors in electrical communication is the same,* it being of course understood that we refer to the potential after the flow, if any, is complete, and not while it is actually occurring.¹

It should be very particularly noted that Poisson's Principle is *perfectly general*; it is true under whatever circumstances the conductors are placed, and whether or not they be subject to inductive influence; it is this that will subsequently be found to give the principle its special value. Also the principle holds, not merely for the surface of the conductor, but right throughout the conducting material. If the conductor be hollow like a tin pot it is true for the inside surface just as for the outside, *the potential at all points alike on the inner surface, the outer surface, and the interior of the metal being exactly the same.*

A particular and very important case of Poisson's Principle is when a conductor is earthed; in that case electricity flows from it or into it according as its potential before earthing was positive or negative, and its ultimate potential is zero (§ 31). In other words *the potential of an earthed conductor is zero.*

[If the conductor be not under inductive influence, this will mean that it is discharged, but if it is under such influence it will have quite another meaning (§ 45).]

It should be carefully noted in all cases what determines the flow when two conductors are connected is *their potentials and not their charges*; if one of the conductors, A, be large and the other, B, small,

¹ The literal meaning of the term *Electrostatics* is that branch of the science which deals with electricity *at rest*. *Electrodynamics* (Part III.) deals with electricity in motion, and to this Poisson's Principle applies only in so far that electricity flows from the conductor of higher to the one of lower potential, but for reasons which will be given in § 149, the flow does not stop and the potentials never become equalised.

a small free charge on B may give it a higher potential than a large charge will give to A ; accordingly when they are connected electricity will flow from B, the one of higher *potential*, not from A, the one of greater *charge*.

Poisson's Principle is in general *not* true for insulators ; thus in an electrified ebonite rod, we have no guarantee that the potential is the same at different parts of the ebonite.

It may help to avoid subsequent confusion to note that when two conductors at different potentials are connected, the flow of electricity from the one of higher potential to the one of lower, eases down the electrical pressure of the former, and raises that of the latter, so that the ultimate common potential of the pair is intermediate in value between the original separate potentials: an exception to this of course occurs when one of the conductors is the earth, for the reason given in § 31.

EXERCISES :—Explain in the light of Poisson's Principle what happens in the following cases :—

- (i) A neutral conductor is earthed.
- (ii) Two neutral conductors are connected by an insulated wire.
- (iii) A negatively charged conductor is earthed.
- (iv) A positively charged conductor is connected with a neutral one.
- (v) A negatively charged conductor is connected with a neutral one.
- (vi) Two conductors having equal positive charges but unequal potentials are connected.
- (vii) Two conductors having unequal positive charges but equal potentials are connected.

33. High and Low, Strong and Weak Potentials. The use of these terms in their proper sense will save much confusion. As explained in § 32, when two conductors are connected, electricity always flows from the one of higher potential to the one of lower—in fact this is *what we mean* by the terms “higher” and “lower”: we say that one conductor, A, has a higher potential than another, B, when electricity tends to flow *from A to B*. And when we say that A has a *stronger* potential than B, we mean that A's potential is *further removed from zero than B's*, and this may not mean that it is higher. For example suppose that A's potential is -20 , i.e., 20 below zero, and B's -10 , then A's will be *stronger* than B's, but at the same time *lower*, because, if A and B be connected, electricity will flow *from B to A*.

34 Gold-leaf Electroscope. Now, before we go any further we must consider this instrument, which is extremely useful in the study of electrostatics. We will describe it in one of its modern forms, in which it is free from the defects of the old-fashioned instruments, so that it will do all that they did very much better, besides doing many things that they could not do at all. It is shown (in vertical section) in figs. 8 and 9, which represent an electroscope devised by the present writer about three years ago.¹ It consists

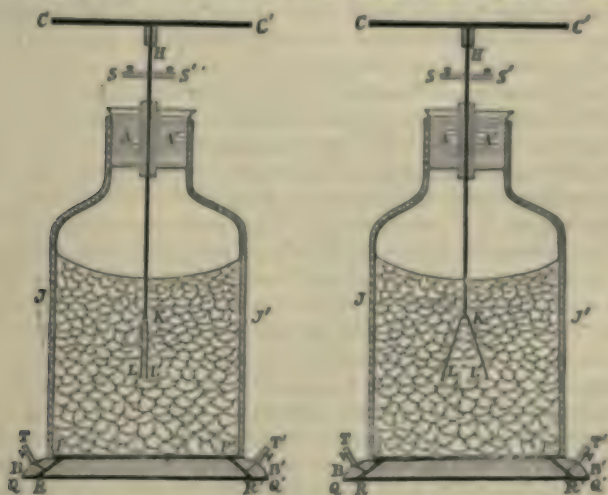


Fig. 8.

Fig. 9.

of a glass jar, J J', open at the bottom and mounted on a wooden base, P P', the rim of the jar fitting into a groove in the base. A brass plate, P B, is fixed on the top of the brass inside the jar, and another, Q Q', underneath the base, the two plates being connected by copper wires, P R, P' R', which pass through the wood. Into the edge of the base are fitted two binding screws, T, T' which are connected by copper wires to P R, P' R', respectively. All round the interior of the jar is a piece of very coarse wire netting, with meshes about three-

¹ Instruments of this pattern are now supplied by Messrs. Thos. Laurie, 13, Paternoster Row, London.

quarters of an inch square, which is soldered on to the plate PP' . It will thus be seen that the netting, the two plates, and the binding-screws, are all in electrical connexion, so that they are electrically *one* conductor. The mouth of the jar is fitted with an india-rubber bung, $A A'$, in the middle of which is fixed an ebonite plug, and through a hole down the centre of the ebonite passes a brass rod, HK , which is fixed so that it cannot slip down. At the bottom, K , of the rod and perpendicular thereto is fixed a piece of brass about $\frac{3}{4}$ inch long, $\frac{1}{2}$ inch high, and $\frac{1}{4}$ inch broad; this cannot be seen in the diagram because it sets perpendicular to the plane of the paper. On this piece of brass are gummed two gold leaves, L, L' , one on each side, each leaf being about $\frac{3}{4}$ inch broad and $1\frac{1}{2}$ inch long; the length, however, should be such that when they are stretched out horizontally they do not reach the netting. When the instrument is not in use the leaves hang close together as in fig. 8, but in many experiments with it they open out more or less as in fig. 9; they are then said to *diverge*. Two binding-screws, S, S' , are fixed to the brass rod as shown, and the top of the rod is surmounted by a circular brass plate, CC' , called the *disc* or *cap*: this should be made to lift off, as for some purposes the instrument works best without it. It will now be seen that the cap, the screws, S, S' , the rod, HK , and the leaves, L, L' , constitute electrically *one* conductor, which is completely insulated from the netting, etc. by means of the india-rubber bung and ebonite plug.¹ The instrument thus consists essentially of two conductors, which may for shortness be spoken of respectively as *the leaves* and *the netting*, completely insulated from one another. In most experiments the instrument simply stands on the table, in which case the netting is earthed by means of the table, floor, etc.; in some experiments, where exceptionally good earthing is desirable, a piece of copper wire may be run from one of the terminals, T, T' , to a gas- or water-pipe. If in any experiment it be required to insulate the netting, it can be done by simply standing the instrument on an insulating stool.

35. Principle of the Action of the Gold-leaf Electroscope.

This instrument is used for a great variety of purposes, but all of them turn upon *one fundamental principle*. We shall not attempt to explain the why and the wherefore of the principle in question, but

¹ There is no absolute necessity for the ebonite plug, but it improves the insulation.

shall take it as a plain experimental fact. Let us see, then, what it is:—Set the electroscope on an insulating stool and connect the terminals, S and T, by a copper wire, so that the leaves and netting become *one* conductor. Beat the cap well with india-rubber; it becomes charged positively, and if a positively charged pith ball electroscope be held over it the pith ball is strongly repelled. *But no movement whatever takes place in the leaves, L, L'; they continue to hang side by side, as in fig. 8.* Now in charging the cap positively we have imparted to it, and of course to the leaves along with it, a certain positive potential; also, since the leaves and netting are *one* conductor by virtue of the copper wire, we know by Poisson's principle that *the potential of the netting is the same as that of the leaves.* The experiment therefore tells us that *when the leaves and netting have the same potential the leaves do not diverge.* If the cap had been beaten with fur instead of india-rubber the same thing would have happened, the leaves and netting now both acquiring the same negative potential. The experiment may be made more striking if instead of merely beating the cap, the terminal S be connected by a wire to a strong electrical machine: on working the latter, the leaves and netting acquire a very strong potential, and by holding the knuckle over the cap, sparks an inch or two long may be taken off, but the leaves and netting have equal potentials and not the least divergence occurs.

Now still keeping the instrument on the insulating stool, take away the wire connecting S and T. Take two conductors, A and B, each mounted on an ebonite support and provided with a binding screw. Connect A to the leaves by joining its screw to the screw S of the electroscope, and connect B to the netting in a similar way by means of the screw T. First let A and B *touch* and charge them: the leaves do not diverge, for now they and the leaves and netting are one conductor, and the potential of all four is, by Poisson's Principle, the same. Now separate A and B and charge A a little more, leaving B alone. *The leaves at once diverge.* In charging A a little more we have strengthened its potential, so that there is now a difference of potential between the leaves and the netting; and the experiment therefore tells us that *when there is a difference of potential between the leaves and netting the leaves diverge.* Again, charge A more strongly still: *the leaves diverge more*; this experiment tells us that the greater the difference of potential between the leaves and the

netting, the greater is the divergence. Hence the principle of the instrument is that *a divergence of the leaves indicates a difference of potential between the leaves and the netting, and the amount of the divergence indicates the amount of that difference.* The electroscope is, in fact, simply an *electrical pressure gauge*.

QUESTION.—If the leaves be made to diverge by charging the conductors A and B to different potentials, and then A and B be connected by means of a brass rod held on an insulating handle, how will the leaves behave? Give a reason for your answer.

It should be noticed that when we speak of the potential of “the leaves” we include the cap and any conductor in electrical connexion with the leaves, either by touching the cap or by being wired to one of the screws S, S', for all these must by Poisson's Principle be at the same potential. Similarly, when we speak of the potential of the “netting” we include the plates P P', Q Q', and any conductor in electrical connexion with them, either by touching Q Q' or being wired to either of the terminals T, T'.

It should be observed also that the divergence of the leaves does not in itself tell us whether their potential be *higher* or *lower* than that of the netting; it merely tells us that there is a *difference*, and indicates the extent of that difference.

The student is again cautioned against attempting at this stage of his studies to explain the principle theoretically; it must be taken as an *experimental fact*, in the same way as the fundamental facts of attraction and repulsion.

36. Electroscope with Netting Earthed.—If the electroscope be placed on an insulating stand and (the leaves and netting being unconnected) the cap be charged, this charge acts across the air in the jar and renders the potential of the netting different from zero, though not equal to that of the leaves. This complicates matters very much; hence, in the vast majority of experiments with the instrument, the netting is kept earthed by allowing it to stand on the table; in that case, by Poisson's Principle, *the potential of the netting is always zero, whatever may be done to the cap, leaves, etc.,* and hence the principle of § 35 takes the simpler and more practically useful form: *A divergence of the leaves indicates that their potential is different from zero, and the amount of the divergence indicates the strength of the potential.* Here, again, when we say “the leaves”

we, of course, include the cap and any conductor in electrical connexion. The divergence does not show whether the potential is positive or negative; this, however, seldom matters, as we generally know beforehand whether we are working with positive or negative potentials, and if not we can—should it be necessary—find out by the method of § 39.

It should be noticed that the principles of this and the preceding sections are *perfectly general*, there are no exceptions to them whatever, and it makes no difference whether the potentials dealt with are due to free charges or to external influences.

In all that we shall in future say about the gold-leaf electroscope it must be distinctly understood, unless the contrary is specified, that *the netting is supposed earthed*; if not, the instrument will in general behave quite differently from what is stated.

37. How to Charge the Electroscope Freely. It frequently happens that we require the leaves of the electroscope to have a free charge. This is easily done. To charge them positively we beat the cap with india-rubber, to charge them negatively we beat it with fur. As, however, constant beating and rubbing does not improve the instrument it is best to beat an insulated metal ball with these respective substances and transfer a charge by contact. A very feeble charge is sufficient; if too strong the leaves are apt to be wrenched off. A positive free charge gives the leaves a positive potential, a negative free charge gives them a negative potential; in either case their potential becomes different from zero, and they diverge in accordance with the principle of § 36.

The following is a very striking experiment. Stand the electroscope on an insulating stool, and earth the leaves by running a copper wire from one of the terminals, S, S', to a gas-pipe. Charge a metal ball and touch one of the terminals, T, T', with it. The potential of the netting then becomes different from zero, while that of the leaves remain zero because they are earthed; hence, in accordance with the principle of § 35, the leaves diverge.

38. Potential of Electroscope due to External Influence. Take a neutral electroscope: the potential of its leaves is zero, which means that their electrical pressure is the same as the electrical pressure of the earth and of all neutral bodies. Now take a positively and freely

charged body, say a glass rod rubbed with silk : this has a positive potential—that is, its electric pressure is above that of neutral bodies. Hold the said body over the cap of the electroscope, a foot or so from it : *the leaves diverge*. The reason is that the cap and leaves experience the effect of the increased electrical pressure, which acts across the dielectric (that is the air) so that their potential becomes raised ; the potential of the netting, on the other hand, remains zero, and the divergence takes place in accordance with the principle of § 36. The nearer the body is brought to the cap the more is the increased electrical pressure experienced, the more the potential of the leaves is raised, and the more they diverge. If the body (it not having been allowed to *touch* the cap) be taken away, the leaves no longer experience the increased pressure, and they collapse.

A potential produced by external influence, as in this case, is called an *impressed* or an *induced* potential (cf. § 41).

The electroscope having the induced potential is sometimes loosely said to be “charged” by induction ; but it must be carefully borne in mind that, taking the cap, rod, and leaves as a whole, they *are not charged at all*, that is, there is no excess or deficit of electricity in them, for no electricity can flow from the charged body through the air. As will be seen in § 49, the leaves and cap taken separately are charged in opposite ways, but this is a secondary matter—the essential point is that *the divergence is due to increased electrical pressure communicated to the cap and leaves of the electroscope across the dielectric, whereby their potential is raised*.

If we employ a *negatively* and freely charged body, its potential is negative—that is, its electrical pressure is *below* that of neutral bodies ; in this case the cap and leaves will experience the effect of *diminished* pressure, their potential will be *lowered* so as to become below zero, and again the leaves will diverge in accordance with the principle of § 36.

39. Simplest Use of the Gold-leaf Electroscope. The simplest uses to which this instrument is put are to determine the *existence* and *character* (i.e., whether positive or negative) of a free charge on a body. It thus serves the same purpose as the pith ball and rods (§ 20), but is far more delicate.

To detect the *existence* of a charge, we simply hold the body to be examined over the cap : if the leaves diverge the body is charged,

if not, it is neutral. The divergence is, as already explained (§ 38), due to the potential acquired by the leaves.

This does not determine the *character* of the charge. To do this we begin by charging the electroscope positively (§ 37), so as to give it a free positive potential. We then hold the body over the cap, taking care to approach it gradually from a distance. Now the student will learn as he proceeds that if under these circumstances the leaves diverge *more*, it affords conclusive evidence that the body was at positive potential. Hence, since in the present case there are no external influences whereby the body might acquire a potential, it must (cf. § 43) have a *positive charge*.

If under the same circumstances the leaves diverge less or remain unaffected, the student will further learn that the evidence is unsatisfactory. In that case we discharge the electroscope by touching the cap with the fingers and give it a free *negative* charge; we then hold the body over, and if the leaves now diverge more, then by the same argument we know that the body has a negative charge.

If the leaves diverge less in *both cases* we are left in doubt: practically, however, this never happens unless the body under examination be *neutral* (see § 59).

The reason for bringing the charged body slowly towards the electroscope from a distance is to avoid the risk of a sudden reversal of the potential of the leaves, before we have time properly to observe their behaviour.

It should be noticed that all these actions primarily depend upon the *potential* of the body. If the body be, as we have supposed, not under the influence of external electrification, the existence and character of its potential depends simply upon its charge (§ 43), so that the method is valid; if there be external influence, the method is valid as respects *potential* but not as respects *charge*; it is, however, then seldom employed.

In practice the best way is to employ three electroscopes, one neutral, one charged positively, and one negatively, placing them several feet from one another so as to avoid inductive action between them; the body to be examined is then held first over the neutral one, and if the leaves do not diverge there is no need to go further. But if they do it is held in turn over the positive and negative one, and whichever diverges *more* tells us the character of the charge.

EXERCISES:—1. How would you show that a piece of metal when rubbed with flannel is charged with electricity, and how would you test whether the charge is positive or negative?

2. An electroscope is standing on the table and its leaves are diverging. Describe and explain what experiment or experiments you would perform in order to ascertain whether their potential was positive or negative.

40. To test the Strength of the Potential of a Conductor. If a conductor, not at zero potential, be put into electrical connexion with the leaves of the electroscope, they diverge. The conductor, cap, leaves, etc., all acquire the same potential (Poisson's Principle), and the amount of the divergence indicates the strength of that potential (§ 36). But it must be remembered (§ 32) that when the connexion is made, a charge (positive or negative as the case may be) passes from the conductor into the cap, rod, and leaves, thus weakening the potential of the conductor so that the potential measured by the divergence is not the *original* potential of the conductor. To render this sense of error as small as possible, *we use the instrument without the cap*, in which case it takes but a very small charge, and we may then in general reckon that the divergence of the leaves indicates the original potential of the conductor.

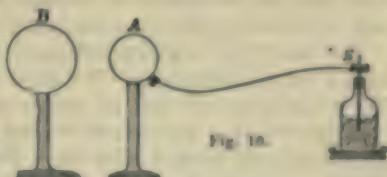
In practice the best way is to take off the cap, place the electroscope several feet from the conductor and screw into one of the terminals, S, S', a long copper wire to whose other end is soldered a round brass ball or knob about $\frac{1}{4}$ inch diameter. The wire is then held (near the knob) by a pair of insulating tongs,¹ and the knob made to touch the conductor; the leaves at once diverge, the amount of divergence indicating the strength of the potential. This device is termed the *knob test*.

REMARK.—We have seen that the operation is accompanied by a flow of a charge into the leaves. Both leaves become, therefore, similarly electrified, and their divergence used always to be, and still frequently is, explained as simply due to the repulsion of similarly electrified bodies (§ 18). This view is, however, apt to mislead, and it is best not to dwell too strongly upon it. Anyway it represents only *part* of the truth, for the motion of each leaf depends not only on itself and its companion, but upon the *whole electric field within*

¹ Insulating tongs are simply a small pair of spring pincers or pliers mounted on an ebonite handle.

the jar, to the condition of which the netting contributes a very important part.

41. Free and Induced Potential. Take an insulated conductor, A (fig. 10),¹ provided with a binding-screw, place it several feet from the electroscope, and run a copper wire from the binding-screw to one of the terminals S, of the instrument. Then perform the following experiments :—



EXPERIMENT 1. Give a free positive charge to A :² the leaves diverge. A now has a *positive* potential, and it is a *free* potential—that is, it is due to A's proper charge and not to external influence.

EXPERIMENT 2. Discharge A by earthing : its potential is reduced to zero and the leaves collapse. Repeat experiment 1, this time giving A a free negative charge : the leaves now diverge at free negative potential.

EXPERIMENT 3. Discharge A so as to make a fresh start with everything neutral. Take another insulated conductor B, give it a free + charge, and bring it gradually towards A, but do not allow it to touch ; also do not bring it near enough for a spark to pass (see § 67). The leaves of the electroscope will diverge and will do so more and more the nearer B approaches A. This shows that A acquires a potential which becomes stronger the nearer B approaches it. Now remove B : the leaves at once collapse, showing that the potential of A is reduced to zero. It is evident, therefore, that A has acquired no charge, as indeed it could not, because it is separated from B by the air, which is an insulator. *The potential of A was simply due to the external influence of B transmitted across the dielectric ; it is an impressed or induced potential* (cf. § 38). The body B having a free + charge has an electrical pressure above that of the originally neutral conductor A, and by bringing B near, this increased pressure is transmitted across the dielectric, and falling upon A raises its potential. The potential acquired by A is therefore positive.

¹ The shape of A and B is immaterial.

² B is absent in Experiments 1 and 2.

QUESTION.—What experiment would you suggest to prove that it really *is* raised and not *lowered*? (Cf. Ex. § 39.)

EXPERIMENT 4. Discharge everything and repeat Experiment 3, only charging B negatively instead of positively; the same results will be observed, this time A acquiring a *negative* induced potential.

The body, B, to whose influence A's induced potential is due, is called the *inducing body*. We have supposed it to be a conductor, but a *non-conductor acts in exactly the same way*: in Experiment 3 we might employ a glass rod rubbed with silk, and in Experiment 4 an ebonite rod rubbed with fur. But the body A must be a conductor, otherwise the action, though essentially similar, is not at all well marked.

In the above experiments, all the electroscope does is to serve as an electrical pressure gauge, whereby we can practically detect the changes of potential; if we do not use the electroscope these changes will occur just the same.

We thus arrive at the following very important result:—A conductor may acquire a potential in two distinct ways.

1. As the result of its own charge—*i.e.*, of an actual excess or deficit of electricity in it: this is called a *free potential*.

2. As the result of external electrical pressure brought to bear upon it across the surrounding dielectric: this is called an *induced* or *impressed potential*.

It will be observed that in the foregoing experiments we have directed that the electroscope be placed several feet from the conductors: the reason is that it may not receive any appreciable potential from the influence of A or B *apart from the wire connexion*—that is, no induced potential from the direct action of B or A on the leaves across the air, which would needlessly complicate the conditions. We shall find as we go on that it is very usual to set the electroscope some distance from the bodies under examination.

It must be most carefully noticed that when a conductor has only an induced potential it has *taken, as a whole, no charge whatever*, that is, no excess or deficit of electricity; it simply possesses its stock amount (cf. § 38).

42. Co-existence of Free and Induced Potential.

EXPERIMENT 1. Connect the conductor A, fig. 10, to the electroscope as in § 41, and give it a free + charge: the leaves diverge

at + potential. Now give B a free + charge, and (without discharging A) bring B near A: the leaves diverge *more*, we are therefore raising A's potential. Then take B away: the leaves fall back to the position they had before B was brought near. When B is near, the potential of A is made up of two parts, one due to A's own charge and one due to the action of B across the dielectric; the former is its *free potential*, the latter is *induced*. The total potential of A is the sum of these two, and it is this total potential that is indicated by the divergence of the leaves. The nearer B is brought to A the higher is the induced potential while the free potential remains unaltered, and therefore the higher is the total potential, so that the leaves diverge more. When B is taken away the induced potential disappears, and there remains nothing but the free potential.

EXPERIMENT 2. Repeat, charging A and B *both* negatively. The same results are observed. Here both the free and induced potentials are negative. The approach of B *lowers* the total potential of A (§ 33); but as A's original potential is negative, this lowering means strengthening, and therefore the leaves diverge more.

EXPERIMENT 3. Discharge everything and make a fresh start. Charge A positively: the leaves diverge at + potential. Now charge B negatively and bring it gradually towards A from a distance. The leaves diverge less and less, until when B arrives at a certain position (call it P) they *do not diverge at all*. When B approaches nearer than P they again diverge and continue to do so more and more the nearer B gets to A.

Now, remembering that the divergence indicates the strength of the total potential of A, it is easy to explain all this. Throughout the process the free potential of A is + and its induced potential is -, so that the two tend to *weaken* one another, and the total potential is their *difference*. When B is farther from A than P is, the free potential gets, so to speak, the best of it and the total potential is still positive, though weaker than the original free potential. As B approaches P the weakening effect of the induced potential becomes more and more felt, until at the position P *the induced potential exactly destroys the free, and the total potential is zero*. When B gets nearer than this the induced potential gets the best of it, and the total potential becomes negative, this negative potential growing stronger and stronger as B gets nearer A.

EXPERIMENT 4. Repeat Experiment 3, charging A negatively and B positively. Similar results are observed, and the explanation is the same making due allowance for the interchange of the + and - potentials: the student should think out the details of this case for himself.

EXERCISE (1899):—An insulated electrified ball is brought near the knob of an electroscope which is then momentarily touched so that the leaves hang vertically. Explain why the leaves diverge when the ball is now removed either nearer to or further from the knob.

43. When Potential and Charge do and when they do not go “hand-in-hand.” When a conductor is *not* under external electrical influence its potential and charge go, so to speak, hand-in-hand—that is, if it has a potential it has a charge, and conversely; also the character of its potential (positive or negative) is the same as that of its charge (cf. § 39).

But when a conductor *is* under external electrical influence its potential and charge do *not* go hand-in-hand. It may have *no charge and yet a potential* (Experiments 3 and 4, § 41). Or it may have a charge and yet no potential, that is, be at potential zero, as in Experiments 3 and 4, § 42, when the induced potential just destroys the free one. Or it may have a charge of one kind (say positive) while its potential is of the opposite kind (negative) as in these same experiments when the induced potential has more than destroyed the free one. The student should think all this over very carefully in the light of the experiments referred to, as it is sometimes felt to be perplexing.

44. Use of Gold-leaf Electroscope to check the truth of Poisson's Principle.

EXPERIMENT. Take several insulated conductors provided with binding-screws and connect them by copper wires—or for the sake of variety some of them may be allowed simply to touch—anything so as they are in electrical connexion. Set up the electroscope some distance away, and attach to it the copper wire with the small knob as in § 40. Give the set of conductors a free charge. Hold the wire leading to the electroscope in the insulating tongs and make the knob touch a point on one of the conductors: the leaves at once diverge. Now run the knob all over the surface of the conductors,

then it will be found that at whatever place it touches, whether on the main conductors or on the connecting wires, *the divergence of the leaves remains precisely the same*. This is clearly in accord with Poisson's Principle that the potential is the same at all points of the set of conductors.

The experiment is sometimes said to *prove* Poisson's Principle, but it does not so much do that as check or illustrate it; it can indeed hardly be *proved* directly, it must rather be looked upon as a fundamental hypothesis whose correctness is established by the readiness with which it explains electrical phenomena.

It should be observed that it does not in the least matter what *shape* the conductors are. It is very usual to exhibit the



Fig. 11.



Fig. 12.

experiment with a single conductor of the shape shown in fig. 11; it is then found that it makes no difference whether the knob be placed at the point P, in the hollow Q, or at any other point R; the divergence of the leaves is precisely the same.

If the conductor be a metal pot, such as that shown in fig. 12, it makes not the least difference in the divergence of the leaves whether the knob touch the outside of the pot say at P, the inside say at Q or R, or the edge say at S.

These experiments check Poisson's Principle for *free* potential; it is equally easy to check it for induced potential or for a potential partly free and partly induced. We have merely to repeat the experiments, placing electrified conductors in the neighbourhood of the conductors we are examining—the same results are obtained. This should be especially noted; a common mistake is to suppose Poisson's Principle true for free electrification only, and to think that if a conductor A be under the influence of some other electrified body B, the potential of A is stronger, at the end near B than at the end farther away, which is not the case—it is just the same all over.

45. Induced Charge. When an insulated and originally neutral conductor, A, is near a freely charged body, B, then, as we have seen (§ 41), A acquires an induced potential, and is sometimes loosely said to have an "induced charge," though it really has no charge at all.

We now proceed to consider an *induced charge properly so called*. Take an insulated neutral conductor, A, and bring near it a freely and positively charged body, B. While B is near, earth A (by touching it with the finger), then *break the earth connexion* (by taking the finger away), and *lastly remove B*. Then test A, either by the pith-ball electroscope, or still better by the gold-leaf electroscope, as in § 39, when it will be found to be *negatively charged*. So much for the *fact*. Now for the explanation:—When B is brought near the insulated conductor A, the latter acquires a positive potential; we now earth A, this *reduces its potential to zero*. But (since no further change has been effected in A's electrical surroundings) this reduction from a positive to a zero potential can only have happened as the result of some electricity having flowed out of A into the earth, A thus acquiring a deficit, that is a negative charge. After earthing, and before removing B, the total potential of A is zero, its positive induced potential being exactly destroyed by the negative free potential due to its negative charge. Merely breaking the earth connexion makes no difference. But as soon as B is removed the induced potential of A disappears and there remains nothing but the free negative potential due to A's negative charge. In fact, *as soon as B is removed* the negative charge on A becomes a free one, just as surely as if it had been imparted by beating with fur, and accordingly affects the electroscope as explained in § 38. It should be carefully noted that the negative charge is *acquired by A at the moment of earthing*—removing B in no way alters the charge, but simply leaves it free to produce its own potential unmolested by external influence. The negative charge on A is called an *induced charge*, in allusion not to its character (for it is really free as soon as B is removed), but the method whereby it has been produced. The term is therefore not so appropriate as the phrase "induced potential," which we have previously used, since the latter denotes a potential due to external influence then and there in operation.

EXERCISES:—1. What is the reason for breaking the earth contact *before removing the inducing body B*? What would happen supposing B were removed first?

It should be carefully observed that in the foregoing process of charging A inductively the amount of A's induced charge is determined by the fact that the free negative potential due to it must be equal and of opposite sign to the induced positive potential due to B's influence; in other words, *so much electricity must flow out of A when it is earthed as shall ease the total electrical pressure of A down to that of the earth*. Other things being the same, the nearer B is to A the higher is A's induced potential, hence the greater must be the negative induced charge in order to counteract it—thus the induced charge is greater the nearer B is to A. Similarly, also other things being the same, the induced charge is greater, the greater the inducing charge.

EXERCISES:—2. Will it make any difference in the final state of A if it had originally a charge of its own?

3. Will it make any difference in the final state of A if it is earthed *before* bringing B near it?

In what has hitherto been said, we have supposed the inducing body B to be +. The induced charge on A is then -. Had B been - the induced charge would have been +: the student should think out carefully the details of this case.

It will thus be observed that the *induced charge is always opposite to that of the inducing body*; in this respect it is the reverse of a contact charge (§ 15), which is always of the same kind as that of the body which imparts it.

As pointed out in § 41, A will derive an induced potential from B equally well whether B be a conductor or an insulator; hence we can impart an efficient charge from a non-conductor to a conductor by induction though not by contact.

This was the old-fashioned way of charging conductors. If one wished to charge a metal ball negatively, it was the custom, instead of beating it with fur (which takes about a second), to dry a glass rod before the fire, do the same with a piece of silk, rub the rod vigorously with the silk, hold the rod near the ball, touch the ball and then withdraw the rod, the whole process, including the drying, taking about ten minutes. The same method was also adopted for charging the gold-leaf electroscope.

It will be noticed that in all the foregoing discussion we have supposed the body A *acted upon* to be a conductor; the case where it is an insulator is unimportant.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER II.

1. *Electrical Pressure* and its analogy to mechanical pressure. In what respect it differs from mechanical pressure. *The electrical pressure of the earth is constant* (§ 31).

2. **POTENTIAL.** *The Potential of the Earth and of all neutral bodies is zero* (§ 31).

3. *Poisson's Principle* in all its aspects as embodied in the following statement. "*The Potential at all parts of a conductor, or of any number of conductors in electrical communication is the same however they may be electrified or under whatever circumstances they may be placed, provided always it be understood that the electricity in them is at rest—that is, that they are in an electrostatic condition. Also if any two conductors at different potentials be electrically connected, electricity flows from the one of higher to the one of lower potential until their potentials are equalised; while if they were equal to begin with, connection produces no effect whatever*" (§ 32). Particular case of the above when one of the conductors is the earth (§ 31).

4. Principle of the action of the Gold-leaf Electroscope, especially with the netting earthed (§§ 35, 36).

5. Use of the electroscope to test the strength of the potential of a conductor (§ 40) and to check Poisson's Principle (§ 44).

6. Free and Induced Potential (§ 41), and their coexistence (§ 42).

7. Induced charge (§ 45).

EXERCISES ON CHAPTER II.

1. A neutral conductor, A, is connected with the leaves of a gold-leaf electroscope, by means of a wire running from it to one of the terminals, S, S' (fig. 8). A positively charged conductor, B, is placed near A: how will the leaves behave? A is then touched by the finger: how will they now behave? The finger is now removed and B discharged: how will they now behave? Give reasons for your answers.

*2. What experiment would you perform with an india-rubber air-bag to illustrate an induced negative charge?

3. An insulated conductor A is neutral. Near to it is brought a positively charged conductor, B. A is then momentarily touched by the finger, and afterwards B is momentarily touched by the finger; B is then taken away and tested: what will its electrical state be? Also was the potential of A after B was touched the same as if B had been not earthed but taken away?

4. You are provided with an insulated metal ball, an ebonite rod, and a catkin: how would you charge the ball *positively*? Explain what happens at the several stages of the process.

5. You are provided with a stick of sealing-wax and a piece of flannel: how would you, by means of these, charge a gold-leaf electroscope positively?

6. A gold-leaf electroscope is placed on an insulating stand and *the cap is earthed*. The netting is placed in electrical connexion with a neutral conductor, A, mounted on an ebonite support and standing on the table. A positively charged conductor, B, is held near A: how do the leaves behave? A is then earthed: how do the leaves behave? The earth connexion of A is next broken and B is taken away: again how do the leaves behave? Explain all these actions.

7. (1900).—Given two insulated metal spheres, A and B, of which A is positively charged and B is neutral, show how a positive charge may be communicated to a gold-leaf electroscope by means of A and B without A losing any of its charge.

8. Two precisely similar gold-leaf electroscopes are placed a long way apart and their caps connected by a wire. A positively charged sphere is then brought near one of them; will their indications in any way differ, and if so which will show the greater divergence? Also what effect will be produced if either of the electroscopes be momentarily touched by the finger and the charged sphere then removed?

CHAPTER III.

POTENTIAL (continued) AND POTENTIAL-GRADIENT.

46. Condition of the Dielectric surrounding a freely charged Conductor. Consider a freely charged conductor surrounded by a dielectric—say air. The electrical pressure of the conductor makes itself felt at every point in the field ; in other words each point of the field acquires a potential which is + or - according as the charge on the conductor is + or -. If the charge be + the potential becomes *lower* as we recede from the conductor, if - it becomes *higher* ; in either case it becomes *weaker*, and under ordinary circumstances is inappreciable at a distance of one or two feet.

To prove this experimentally we proceed thus :—Place a gold-leaf electroscope two or three yards from the charged conductor and attach to it a long copper wire with a small brass knob at the farther end as in § 40, then holding the wire in the insulating tongs move the knob to and fro in the field, when it will be found that the nearer it approaches the conductor the more the leaves diverge ; this shows that the potential of the dielectric weakens as the distance increases.

QUESTION :—What addition is required to the experiment to prove that the potential at any point of the field is of the same sign as the charge in the conductor ? (Cf. Ex. 2, § 39.)

Every one knows the meaning of the term *slope* or *gradient* as applied to a hill, and in the same way we may speak of the *potential-gradient* in an electric field. If as we travel in imagination through the field, we pass from a place of higher to one of lower potential, we are on a down-gradient, and *vice versa* ; while if the potential is uniform throughout any part of the field, we may speak of that portion as at a dead level of potential. Poisson's Principle tells us that all parts of a conductor are at a level in this sense.

What has above been said may be expressed thus:—There is a potential-gradient in the dielectric surrounding a freely charged conductor, *the down-gradient being away from the conductor if the latter be positive and towards it if negative.*

All the remarks of this article apply when the charged body is a non-conductor, only of course the potential of the body itself is now in general not the same throughout.

47. Condition of the Dielectric inside a freely charged hollow conductor. This is a very important case not included in § 46. Consider a completely closed hollow conductor—*e.g.*, a tin pot with the lid on—and let it be insulated and freely charged. Then the air (or other dielectric) inside will experience electrical pressure and therefore acquire a potential. But how does this potential vary from point to point? Now it can be proved by mathematical reasoning that *it does not vary at all, it is the same at all points, and moreover is the same as that of the actual conductor.*

The study of hollow conductors constitutes rather an important branch of Electrostatics. The form commonly employed is known as *Faraday's ice-pail*; it is simply a tin pot (fig. 12) *without* a lid, and should be fairly deep in comparison with its diameter,¹ in which case the potential is practically uniform as soon as we get well inside the pot. Near the opening the potential is weaker.

Indirect experimental proofs of the above theorem will be found in § 50, but no satisfactory *direct* one can be devised.

It should be noted, in order for the theorem to be true, it is not necessary for the conductor to be of continuous metal plate; wire gauze answers just as well, provided that the meshes be not extremely coarse, say not more than $\frac{1}{4}$ inch square.

EXERCISE:—An open tin pot about 4 in. broad and 9 in. high is insulated and charged positively. Trace the changes of potential at a point conceived to start outside, pass through the metal near the bottom, travel up through the middle of the pot, and come out at the mouth.

48. Case of a Hollow Conductor not freely charged. The theorem of the preceding article is equally true, if instead of the conductor merely possessing a free charge, there be charged bodies *outside* it, provided that if it be in the form of an open pot, such

¹ A depth equal to about twice the diameter answers very well.

bodies are placed well below the level of the mouth, so that the electrical pressure emanating from them may fall on the metal and not on the internal dielectric.

If, however, there be charged bodies *inside* the conductor, the theorem is emphatically *not* true.

49. Inductive Displacement. In § 45 we have explained how by earthing a conductor when under external electrical influence an induced charge is imparted to it.

Let us now consider what happens when the conductor is *insulated*. In fig. 13 let a positively and freely charged conductor, C, be brought near an insulated and originally neutral conductor, A N B. Then

it is found by experiment that the portion N B becomes positively charged and the portion N A negatively. The best way to prove this is to have the conductor A B made in two approximately equal parts (mounted on separate supports) and allow them to rest against one another; if while under the influence of

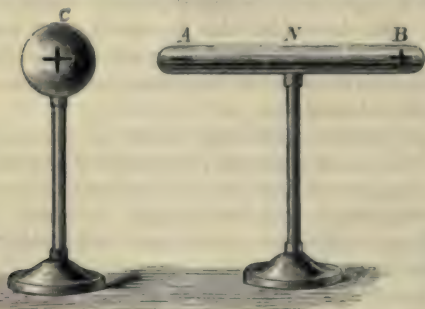


Fig. 13.

C these parts be separated and then removed from C, and tested as in § 39, the end B will indicate a positive and the end A a negative charge. If now (while still away from C) the two parts be made to touch each other and again tested either separately or together, they will be found perfectly neutral.

The conductor A B may be of any shape, and it is frequently convenient to employ two insulated metal balls, A and B (not necessarily of the same size), and which may either rest in contact (fig. 14) or be connected by a wire (fig. 15). When C is placed as shown, the near one A becomes negatively and the far one B positively charged, while the two together are not charged at all.

Now, all this is readily explained as the result of electrical pressure acting from C across the dielectric. To make it clear, let us (taking

the case of fig. 13) consider the potential of C 's field before the balls A and B are placed in it. In fig. 16 let the dotted lines represent the portion of the field where the balls A and B are going to be placed; then, as explained in § 46, the potential on the near side, PQR , is higher than the potential on the far side, $P'Q'R'$. Consequently when the balls

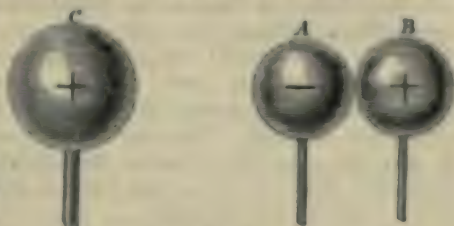


Fig. 14.

are introduced we are applying greater electrical pressure to A than to B , the result of which is to force electricity out of A into B ; in this way A acquires the negative and B the positive charge. It is clear that these charges must be equal, since B merely acquires what A loses. Electricity is simply *displaced* from A into B (or in the case of a single conductor from the side near C to the side away from it), and the phenomenon is therefore spoken of as *inductive displacement*, or simply *displacement*.



Fig. 15.

When the balls are separated and C removed, each retains the charge thus acquired, and when

(C being away) they are brought together again, there being now no external influence to maintain the displacement, the excess from B re-enters A , making good the deficit, and both become neutral.

EXERCISE:—1. What would happen supposing C were removed or discharged *before* separating A and B ?

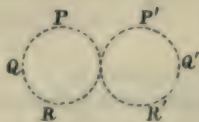
It is very important to observe that the two balls *taken together* have no charge, and also that when a single insulated conductor (as A B , fig. 13) is brought under inductive influence the conductor *as a whole* receives no charge. To speak, therefore, as used to be and still often is done, of such a conductor as "charged by induction" is misleading; the modern statement that *each part of the conductor is charged while the conductor as a whole is merely subject to inductive displacement* is far more appropriate.

Another point should be very carefully noted. *Before* the conductor A N B, fig. 13, or balls (figs. 14 and 15) are placed in the field the potential near C is higher than that farther away. But as soon as conducting material takes the place of the dielectric no such difference of potential can exist (Poisson's Principle), so that the potential on the near side of A is just the same as on the far side of B; indeed the potential is the same throughout the entire material. The displacement of electricity from A to B may be regarded as easing the electrical pressure on A and increasing that on B, so that whereas *before* the flow there was

a difference of pressure, *after* the flow there is none, the potential becomes uniform throughout and of some value intermediate between those of the dielectric at Q and Q' (fig. 16), prior to the introduction of the balls. It is this uniform potential which constitutes the induced potential (§ 41) of the balls.



Fig. 16.



If the inducing body, C, be negatively charged, all the foregoing remarks apply with the necessary changes. By § 46 the potential of the dielectric on the far side P' Q' R' (fig. 16) is now greater than on the near side P Q R; hence when the balls are introduced the displacement of electricity occurs from B to A, so that A acquires a positive and B a negative charge, while both acquire a uniform induced negative potential.

If, in fig. 15, B be the rod and leaves of an electroscope instead of a ball, the divergence of the leaves indicates the common potential of A and B. But, as above explained, electricity has been displaced from A to B, thus easing off the electrical pressure of A and making it slightly lower than that of the dielectric which originally occupied A's place, hence the divergence does not *accurately* measure the potential of the dielectric at that place.

Taking the case of a single conductor, as A B, fig. 13, then while

insulated and under the influence of a + inducing charge on C it has a + induced potential. If it be then earthed sufficient electricity runs out of it to reduce its potential to zero, thus leaving a deficit. This becomes the case already contemplated (§ 45), the deficit being the negative induced charge.

It should be noticed that in no case is it necessary for the *inducing* body C to be a conductor. It is sometimes said that the body A B acted upon must be, but this is not the case. If A B be an insulator, inductive displacement occurs in the same way as for a conductor, but to a less extent. Moreover, *earthing* an insulator does not reduce its potential to zero, though it may more or less weaken it; the induced charge (§ 45) is therefore much less.

In the older text-books a view of inductive action was commonly given depending upon a theory of so-called "bound" and "free" charges; this theory is now known to be erroneous and is here merely mentioned to caution the student against it.

EXERCISE.—2. (1903.) Explain what is meant by difference of potential. How are the charge and the potential of an insulated body altered by bringing a positive charge near it?

50. No Inductive Displacement in a Field of Uniform Potential. The argument of § 49 shows that inductive displacement is due to one part of the conductor occupying a portion of the field P Q R (fig. 16), which was originally at *different potential* from the part P' Q' R' occupied by another portion. If, therefore, the original field be one of uniform potential, there will be no inductive displacement. Thus in fig. 17, when an insulated uncharged metal ball A is introduced into a charged metal pot B, the ball experiences the same electrical pressure all over, so that there is no influence tending to drive electricity from one part of it to another, and no part of it acquires any kind of charge. Moreover, there being no displacement, there is nothing tending to modify the electrical pressure, so that *the potential of the ball is precisely the same as that of the air before its insertion, and therefore the same as that of the pot.* But if we now

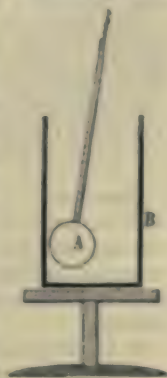


Fig. 17.

connect the ball to some neutral conductor *outside* the pot, and therefore in a region of different potential, displacement occurs; if then the connection be broken, and the ball taken out and tested, it will be found to possess a charge of opposite kind to that of the pot.

EXERCISE:—1. Two insulated metal balls are set touching one another inside a large tin case, and the door is then closed. The case is provided with a small hole in the side near the bottom, and through this passes an ebonite rod which is attached to the base of the support on which one of the balls is mounted, the object being to permit of separating the balls without earthing the case. The whole is placed on an insulating stand, and a strong positive charge given to the case. The balls are then separated by means of the ebonite rod, and then taken out and tested by a neutral gold-leaf electroscope. What will happen? Give reasons for your answer.

The following is a standard experiment in illustration of the principle of this article:—Take a large gauze cage provided with a door and put a gold-leaf electroscope inside it so that the earth-plate ($Q\ Q'$, fig. 8) stands on the metal work of the cage while the cap does not touch the cage, but is simply surrounded by the enclosed air. Shut the door, place the whole on an insulating stool, and charge the cage strongly; *the leaves of the electroscope do not diverge.*

The reason is as follows:—The cap and leaves are surrounded by the air within the cage, and therefore just like the ball A in fig. 17, they acquire the potential of the cage. Also the netting being in conducting communication with the cage, acquires the potential by Poisson's Principle. Hence the leaves and netting are at the same potential, and therefore (§ 35) there is no divergence.

EXERCISES:—2. If the electroscope is in the condition just explained, and we push a long brass rod with a brass knob at the outer end through one of the meshes of the cage (taking care that it does not touch the latter), and make it touch the cap of the electroscope, how will the leaves behave (i) when the rod is insulated? (ii) when earthed?

3. In the preceding question, if the rod be afterwards removed, will the leaves of the electroscope be charged, and if so in what way?

4. Two uncharged brass balls, A and B, each mounted on a long ebonite handle are held inside a neutral insulated metal pot, and made to touch

each other but not the pot. A positively charged ball, C, is then held outside the pot, and while there the balls A and B are separated and then withdrawn from the pot. Will either of them have a charge? (See § 48.)

In practice it is sometimes advisable to screen off an electroscope from the action of electrified bodies in the neighbourhood. To do this it suffices to cover the instrument with a metal cage whose lower edge rests on the table on which the electroscope stands; supposing the electroscope uncharged, the inside of the cage is (§ 48) at uniform potential (zero) and the netting is the same so that no divergence occurs. Even if the electroscope be charged the *external bodies* produce no effect upon it.

51. No Charge on the Inner Surface of a Freely Electrified Hollow Conductor: Emptying out. When an uncharged ball, A, is held inside a freely charged pot, B, as in fig. 17, we have seen in the preceding article that the potential of the ball is equal to that of the pot. If, therefore, we make the ball touch the inside of the pot we shall be merely connecting two conductors which to begin with are at equal potentials, and therefore, by Poisson's Principle, nothing whatever will happen, there will be no flow of electricity either from the pot to the ball or *vice versa*, and accordingly, if we take the ball out and test it by a neutral gold-leaf electroscope, we shall find it to be *perfectly neutral*. Now the ball while touching the inside of the pot is, electrically considered, simply a part of that inside; the fact therefore, that when taken out and tested it is found to possess no charge proves that there is *no charge on the inside surface of a freely electrified hollow conductor*; the entire excess or deficit of electricity resides on the *outside surface*.¹ This fact, which is of great importance, is one of several which were originally discovered by Faraday in respect of hollow conductors. It is scarcely needful to point out that it is only true for places well inside the pot, it is not true near the edge; if, however, the pot were furnished with a metal lid, so as to form a completely closed conductor, it would be true throughout the entire interior.

¹ We may here mention what will receive full consideration in the next chapter—*viz.*, that there is no charge in the *actual material* of any conductor.

It should be carefully noted that if the ball be charged to begin with, and then made to touch the inside of the pot, it makes no difference in the final result. The charge on the ball is *completely transferred* to the pot, passing through to its outer surface, and this is true even if the pot be charged at the outset, no matter how strongly. This process is known as *emptying out the charge* from the ball; it is the only known method whereby a charge can be *completely* transferred from a conductor to another insulated conductor: if the ball be made to touch the outside of the pot, or of another ball, the charge is *shared between them*. This emptying-out process will play an important part in some subsequent sections.

On reviewing the foregoing arguments it will be seen that the absence of charge on the inner surface of the conductor is a necessary consequence of the uniformity of potential of the internal dielectric. Now in § 48 we have learned that this internal potential is also uniform when the conductor is *not* freely charged, *provided there are no charged bodies inside it*: hence *in the latter case also there will be no charge on the inner surface*. This can easily be proved experimentally by touching the inside with a brass ball mounted on an ebonite handle and carrying it to a neutral electroscope.

EXERCISE (1902):—A metal funnel rests with its upper edge in contact with that of a hollow metal cylinder of such length that the end of the stem of the funnel is near the middle of the cylinder, which is supported by an insulating clamp. Some shot charged positively are poured through the funnel into an insulated metal vessel some distance below the cylinder. If the cylinder and vessel are unchanged at the start, what will be their final charges?

52. Hollow Conductor with a charged body inside it: Faraday's Ice-Pail Experiment. In this case (§ 48) the potential of the internal dielectric is not uniform and the arguments of the preceding articles do not apply. The case must therefore be examined separately: its investigation constitutes the most important of Faraday's "ice-pail" experiments, and is generally known as *the ice-pail experiment*. It is as follows:—

On the cap of a neutral electroscope (fig. 18) place a neutral metal pot. Take a brass ball mounted on a long ebonite handle, give it a charge which we will suppose positive and equal to Q , and hold it in the pot as shown, the pot will then acquire an induced

potential (§ 41) and the leaves will consequently diverge. Now move the ball about inside the pot (taking care that it does not touch) and it will be found that (so long as we keep it well below the level of the mouth) the divergence remains quite unchanged, thus showing that the induced potential of the pot is independent of the position of the ball within it. This is an important preliminary, but now comes the *main* part of the experiment:— Having noticed the divergence just mentioned, make the ball *touch* the inside of the pot so as (§ 51) to empty the charge, Q , completely into the latter: *the divergence of the leaves will not in the least alter*. Now when Q is emptied into the pot the latter of course acquires a free potential in place of the original induced one, and since the ball is completely discharged it may be removed from the pot without making any difference.

Our final conclusion, therefore, is that *when a ball having a charge, Q , is held within a metal pot, the potential of the latter is the same as if the ball were absent and the charge, Q , belonged to the pot itself*. There is, however, another aspect of the case to be considered—viz., the charges on the inner and outer surfaces of the pot when the ball is held within it before touching. These charges are, of course, due to inductive displacement, the outside of the pot acquiring a positive charge ($+x$) and inside an equal negative charge ($-x$), and the question is what is the relation between these local charges and the charge, Q , on the ball. To settle this without the introduction of difficult reasoning it is best to resort to another experiment:—

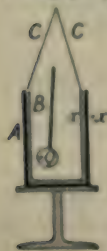


FIG. 19.

Take *two* metal pots, A and B (fig. 19), of which B just fits inside A and place them on an insulating stand as shown. Let the inner one B, be provided with a silk thread, CC, by means of which it can be lifted out of A. Hold the ball with the charge, $+Q$, inside B, then B acts as the inside surface and acquires the charge, $-x$, while A acts as the outer surface and acquires the charge $+x$. Now, still holding the ball inside B, lift B out of A by the silk thread, so that we have B with the charge $-x$ and inside it the ball with



FIG. 18.

the charge $+Q$. Then make the ball touch B, and afterwards test the pair by an electroscope, *when they will be found perfectly neutral*. This shows that $+Q$ has neutralised $-x$ and therefore Q and x must be equal.

We therefore learn that *when a ball having a charge $+Q$ is held inside a metal pot, it produces by inductive displacement an equal charge $+Q$ on the outer surface of the pot and a corresponding charge $-Q$ on the inner surface.*

One more experiment in conclusion. Place a metal pot on an insulating stand, hold within it the ball having a charge $+Q$, and touch the pot with the finger so as to get an induced charge on the pot as in § 45. Then remove the finger, make the ball touch the pot, and test the pair by an electroscope: this will be found perfectly neutral, hence the induced charge on the pot must have been $-Q$, *Earthing the pot in fact simply removes the external charge, leaving the internal unaffected*. It should be noted that this is the only case in which the induced and inducing charges are *equal*; if instead of the pot we use another ball, or if we hold the ball *outside* the pot, the induced charge is *less*.

EXERCISES:—1. (1903.) A charged insulated conductor, A, is surrounded by a closed metallic box. What experiment would you make to show that the charge on the inside of the box is equal and opposite to that on the conductor?

2. A metal pot is placed on the cap of an electroscope. The following operations are then successively performed; state and explain the final behaviour of the leaves in each case:—(i) $+Q$ Charged ball held inside pot and then withdrawn; (ii) $+Q$ Charged ball made to touch inside of pot and afterwards withdrawn; (iii) Pot touched by finger, finger removed, $+Q$ charged ball introduced, pot again touched by finger, finger again removed, and lastly ball withdrawn.

3. (1901.) Given two similar insulated metal pots and a small charged metal ball suspended by a fine silk ribbon, how would you charge the pots (a) with equal charges of the same sign, (b) with equal charges of opposite sign?

53. Electric Screens and Shadows. If a charged body be placed inside an earthed metal pot, the potential of the pot is of course zero, and it is therefore incapable of applying electrical pressure to the external dielectric or to any external body. In other words the pot completely screens the external region from the

influence of internal electrified bodies, thus casting, so to speak, an electrical shadow in much the same way as if we were to place a lighted candle in the pot it would give no light outside.¹

If instead of a pot we employ a broad flat metal plate, and place the charged body on one side of it, not near the edge, the action is very similar; there is a good electrical shadow on the other side of the plate.

EXERCISES.—1. A metal pot is held by insulating tongs a few inches above the cap of an electroscope. A charged ball is then held inside the pot; how do the leaves behave? The pot is then touched by the finger; again, how do the leaves behave?

2. A charged ebonite rod is held a few inches above the cap of an electroscope and a broad tin plate held in the fingers is then introduced between the rod and the electroscope. What effect, if any, will this have on the leaves? Also what will be the effect if, instead of a tin plate, we use one of unelectrified ebonite?

We subjoin a discussion of the following interesting question from the Board of Education Elem. Exam. of May 1894.

"The cap of a gold-leaf electroscope resting on an insulating stool is joined by a wire to the gas-pipe. How will the leaves be affected when a charged glass rod is brought near the electroscope?"

The phrase "near the electroscope" presumably means "over the cap."

Now the cap being earthed is at zero-potential, so that (§ 35) everything depends upon whether or no the *netting* be also at zero-potential.

Now if the cap be of the usual size (about 6 in. diameter), the netting is not well within the electrical shadow of the cap; it therefore experiences electrical pressure from the rod, and its potential (the rod being +) is raised. Hence by the principle of the instrument (§ 35) the leaves diverge.

But if the cap be very big (say 2 ft. diameter—a piece of tin-plate may be laid on it as a convenient substitute), then the netting is well within the electrical shadow, the potential of the netting remains zero, and the leaves do *not* diverge.

If the electroscope be made without a netting, the glass and dirt on it have to act as an indifferent substitute, and its behaviour is more or less after above fashion. But it is somewhat difficult to predict how a *bad* instrument will behave under any conditions whatever.

¹ Of course the light from the candle would shine upwards through the mouth of the pot so that unless the latter was provided with a lid there would be a limited region above the mouth *not* in shadow: *it is precisely the same with the electrical action.*

54. Further Study of Charge and Potential. We have already learned (§§ 41, 42) that a conductor may have a potential due to its own charge (i.e., a free potential), or one due to the influence of other electrified bodies (i.e., an induced potential), or both combined.

There are some further points to study in connection with the free potential of a conductor, and we shall deal with these in the next few sections. It must be understood throughout that the conductor is, unless the contrary is stated, supposed free from inductive influences; it simply has a free charge and a free potential due to that charge.

The subject of the next section is very important, both in itself and as a preliminary to the further studies proposed.

55. To Test the Amount of Charge on a Freely Electrified Conductor. In § 40 we have explained how to test the *strength of the potential* of a conductor. But this does not test the *amount of its charge* any more than the pressure of the air in an india-rubber bag tests the amount of air that it has above or below its stock amount. How then can we test the amount of charge? Let us again consider our bags. If we take *different* bags the increase of pressure is found to depend not only upon the excess of air forced in but also upon the size and shape of the bag, and upon the thickness and quality of the india-rubber. But if we perform different experiments with the *same identical bag*, varying only the excess of air, then the increase of pressure depends only on the said excess,—the greater the one the greater the other. In like manner if we perform different experiments with the *same identical conductor*, varying only the charge, the strength of the potential will depend only on the amount of the charge,—the greater the one the greater the other. Hence we have the following method for comparing the amounts of charge on two freely electrified conductors A and B whatever their size, shape, etc. :—

Take a tin pot and set it on the cap of a gold-leaf electroscope. Empty out the charge of A into the pot, as in § 51, and note the divergence of the leaves. Then discharge the pot and empty out the charge of B into it, again noting the divergence. By § 36 the divergence in each case indicates the potential of the conductor, made up of the pot, cap, rod, and leaves. But since the conductor

is *identically the same in both cases* the stronger potential corresponds to the greater charge. Hence the conductor, which under these circumstances gives the greater divergence has the greater charge.

For practical purposes there is no necessity to make either conductor *touch* the pot, for as pointed out in § 52 the potential of the pot is the same when it is *merely held well inside it*. This is a great advantage, because we can test the amount of charge without allowing any of it to leave the conductor; all we have to do is to *hold the conductors one after another well within the pot*, and the one that produces the greater divergence has the greater charge.

REMARK.—The method of this section enables us to prove more accurately than § 25 the fact that when a body is electrified by friction the body and rubber acquire opposite charges of equal amount. Two metal cans, A and B, are arranged as shown in fig. 20 and insulated from each other. The inner, A, is lined with fur, and an ebonite rod, R, fits closely into it. The outer can B is connected to an electroscope by a wire as shown, or may simply stand on the cap. On twisting the rod R, the leaves do not diverge, showing that the total charge inside the can B, that is the charge on the ebonite and fur together is nil, in other words that the negative and positive charges are equal.



Fig. 20.

EXERCISE:—How will the leaves behave if the ebonite rod be withdrawn?

We proceed to study the relation between charge and potential.

56. To show that two Conductors may have the Same Potential but Different Charges. Take two insulated conductors not exactly alike, say two brass spheres of different sizes, give one of them a charge, place them some distance apart, and connect them by a thin metal rod held in an insulating clamp, so that the charge is divided between them. Then by Poisson's Principle they have the same potential, and of course if tested as in § 44, this will be found the case. Now separate them by removing the wire, then each retains

its potential and charge unaltered.¹ Next hold them one after another in a metal pot standing on the electroscope as in § 55, when *the bigger sphere will be found to produce the greater divergence showing that it has the greater charge.*

Suppose now the charge to be positive, and after the spheres are separated let a small extra charge be given to the small one, but still leaving its charge less than that of the big one. In this way the potential of the small sphere will become higher than that of the big one. If now the spheres be connected, electricity will, by Poisson's Principle, flow from the small one to the big one until their potentials again become equal. We have here then a case where electricity is flowing *from a conductor of smaller charge to one of greater*: this is a common occurrence, but it should be carefully noticed, because students are so apt to fancy that the flow must always be from the big charge to the little one; it must be remembered that what determines flow is the *potential* and not the charge. (Cf. § 32.)

In the same way, if we have a small india-rubber air-bag at high pressure, and a large one at lower, then on connecting them air will flow from the little one to the big one, although the latter may already contain the greater quantity of air.

57. To show that Two Conductors may have the Same Charge but Different Potentials. This of course is a necessary consequence of the theorem of § 56, but the following experiment shows it *directly*:—Take two precisely similar gold-leaf electroscopes, place on one of them a small tin pot and on the other a large one. Take two metal spheres of exactly the same size, make them touch, and give them a charge. Since they are both exactly alike, their charges must be equal. Empty the charge from one into the small pot, and that from the other into the large one, or (§ 55) merely hold one in one pot and one in the other without touching: *the electroscope in connection with the small pot will show the greater divergence. Here the two pots have equal charges, but the small one has the stronger potential.*

¹ The object of placing the spheres at some distance apart and connecting them by a rod instead of merely allowing them to touch, is to ensure that throughout all the stages of the experiment *each sphere simply has the potential due to its own charge*; in the higher parts of the subject it is shown that if the spheres are allowed to touch the potential of each is complicated by the presence of the other; while in contact the potentials would of course be the same by Poisson's Principle, but after separation they would undergo a change so that the reasoning would not be valid: practically, however, the experiment usually works very well in this way.

EXERCISE :—If now an insulated copper wire be run from the outside surface of the large pot to the inside surface of the small one, how will the two electroscopes behave?

58. To show that the Charge on a given Conductor at given Potentials depends on the Nature of the Surrounding Dielectric.

Take two precisely similar conductors (fig. 21) mounted on ebonite supports, each conductor consisting of a brass ball (A, B) surmounted by a brass rod (P, Q). Of these conductors let one, A P, be surrounded simply by air, while the other B Q, is embedded up to nearly the top of the rod in a thick layer, D D, of paraffin-wax. Give the conductor, A P, a charge

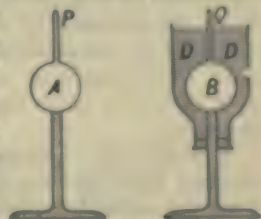


Fig. 21.

and then place it some distance from B Q and connect the ends, P, Q, by a thin insulated metal rod, so that the charge may be divided between the conductors and each acquire the same potential as in § 56. Then separate them by removing the wire, and hold them one after the other in a metal pot standing on an electroscope, when it will be found that *the one embedded in the paraffin-wax produces a greater divergence and therefore has a greater charge.*

This is commonly said to be because the "specific inductivity" or "specific inductive capacity" of paraffin wax is greater than that of air, but this is merely taking refuge in words and explains nothing until we know to what actual property of the dielectric the so-called "specific inductivity" corresponds: this is discussed in the more advanced parts of the subject.

The specific inductivity, not only of paraffin-wax but of all solid dielectric such as glass, shellac, ebonite, etc., is considerably greater than that of air.

EXERCISE :—If the two conductors in fig. 21 receive equal charges, which will have the stronger potential?

59. To show that the Potential of a freely-charged Conductor is weakened by bringing an Earthed Conductor near it. Take an insulated conductor, A, provided with a binding-screw, and connect it by a copper wire to one of the terminals, S, S' (fig. 8), of a distant electroscope. Give it a free charge: the leaves diverge, the

amount of the divergence indicating the potential. Now bring near the conductor A an earthed conductor B, say a metal ball or sheet, or simply the hand: the leaves of the electroscope will be seen to diverge less, and the divergence will diminish the nearer B approaches to A, thus showing a gradual weakening of A's potential. Of course the *charge* on A is not altered in amount by the process. We hence learn *the potential of a given conductor having a given charge is weakened by the presence of an earthed conductor in its neighbourhood*. This is a most important principle, and, as we shall see in § 72, is that on which the action of Leyden jars and other condensers depends.

Now as to the explanation. Let us suppose A's charge positive, so that the leaves diverge at positive potential. Then as explained in § 45, the earthed conductor B acquires a negative induced charge. The latter acting across the dielectric between A and B imparts to A a negative induced potential. The total potential of A is now its original free potential *diminished by the induced one*, so that its actual potential is lower (and weaker) than when B was absent. The nearer B is to A the greater is the induced negative charge and the greater the weakening of A's potential.

If B be insulated instead of earthed (and uncharged), it still weakens A's potential, though in general to a much smaller extent. The explanation is similar. Here, however, we have inductive displacement on B instead of an induced charge, and the weakening effect on A's potential of the negative charge on the near side of B is in a great measure counteracted by the opposing influence of the positive charge on the far side. It is clear from this that in general the bigger B is the more marked will be its weakening effect upon the potential of A, and that in the special case where B is a very thin plate, so that the near and far sides are close together, the weakening effect will be practically *nil*.

EXERCISES:—1. A charged metal ball, A, is connected by a wire to the cap of an electroscope and the leaves diverge. The following operations are then performed in succession; state and explain the behaviour of the leaves in each case: (i) A large uncharged insulated metal ball B is placed near A, (ii) B is touched by the finger, (iii) B is taken away.

2. A (positive) charge is given to the cap of an electroscope, and the leaves diverge. The hand is then held over the cap, and the divergence becomes less. Explain this.

What would happen if instead of the hand you employed an insulated metal ball?

3. In § 39 it was pointed out that in using the electroscope to test the character of a charge on a body, it is not quite satisfactory to rely upon partial collapse of the leaves—we must look for increased divergence. Give at least one reason for this.

60. Electrostatic Capacity. Collecting, now, the several results of §§ 57, 58, and 59, we learn that the potential of a freely electrified conductor depends upon:—

- (1) The amount of its charge.
- (2) Its size (and shape).
- (3) The nature of the surrounding dielectric as expressed by its specific inductivity.
- (4) The neighbourhood of other conductors, especially if earthed.

The ratio of the charge on a given conductor under given conditions to its potential is called its *electrostatic capacity*, or briefly its *capacity*; it is clear, therefore, that the capacity of a conductor depends upon the latter three of the foregoing four items. For a conductor of given shape the capacity is in general greater the larger it is, the more effectually it is surrounded by earthed conductors, and the greater the specific inductivity of the dielectric; as pointed out in § 58, the specific inductivity of all solid dielectrics—*e.g.*, glass, shellac, ebonite, etc., is considerably greater than that of air, so that the effect of surrounding a conductor with any of these is to increase its capacity.

If Q denote the charge on a conductor under given conditions, V its potential, and C its capacity, we have by definition $C = \frac{Q}{V}$, and therefore $Q = CV$, a fundamental relation between the three quantities which is of frequent service.

61. Work and Energy. Whenever a mechanical force is exerted in such a way as to make a body move, *work* is said to be done by the force or by the agent which exerts the force. Thus, a horse does work in pulling a cart, and a steam-engine does work in moving a train. When a stone falls, the weight of the stone (that is, the attraction of the earth upon it) does work, while if a man lifts it the man does work *against* the attraction of the earth; and in general, if a body be placed under circumstances such that a force P acts on

it, and free play be given to the force, the latter will drive the body in a certain direction and thus do work ; while if some outside force Q be introduced so as to drive the body in the direction opposite to that which it would take under P 's influence, then Q does work against P .

Mere force apart from motion does no work : thus, when a weight rests on a table, it exerts a pressure but no work is done. Again, mere motion apart from force implies no work ; when a ball is thrown along the surface of smooth ice, work has to be done to give it a start, but afterwards the ball will travel a great distance without any more force being applied because the ice offers very little resistance to the motion ; and if we could obtain a *perfectly* smooth horizontal surface of unlimited extent, and the resistance of the air could be abolished, it would go on moving for ever without the application of any force, and therefore without any work being done.¹

It is very important to note that the motion which results from the expenditure of work is not always *actual bodily* motion. If we fix a nail in a vice and file it, we exert force and do work, but we do not move the nail from its place. It will be found, however, that the nail becomes hot. Now as explained in treatises on heat, heat itself is due to rapid movement of the particles or *molecules* of a body : in this case, then, the result of the work done is to cause the molecules of the nail to move more rapidly than before, so that *the work produces heat*. It is a very common tendency of work to produce heat, and in all machinery precautions have to be taken by oiling, etc. to prevent this. If the bearings of any machine be rough or not properly greased, then when the machine is driven say, by a steam-engine, much of the work of the engine, instead of producing the proper motion of the machine which we want, produces heat in the bearings which we do not want, and is therefore wasted. This waste is the equivalent of the work done against the resistance or friction of the bearings : by having these smooth and well greased the friction is greatly reduced, and the work done against it consequently much less.

Whenever anything has the power of doing work it is said to possess *energy*. It is usual to distinguish between two forms of

¹ This is Newton's first law of motion, which is fully discussed in treatises on mechanics.

energy, *potential*¹ and *kinetic*. To understand the distinction, let us take an example of each. When a Dutch or "grandfather" clock is wound up, the weight possesses the power of driving the clock, and so doing work—that is, it possesses energy. This energy is due to the fact that it is *raised*, for after it has run down it can no longer drive the clock: it is *energy due to position*, to position in this case *relative to the earth*, and is an instance of *potential* energy. Next consider a train approaching a station with the brakes on. The train is doing work against the friction of the rails, which work is converted into heat: it therefore possesses energy, and this time the energy is due to the fact that the train is moving, it is *energy due to motion*, and is an instance of *kinetic* energy. By *potential energy* we mean, then, energy due to *relative position*, and by *kinetic energy* that due to *motion*. A watch spring when wound up affords a good instance of potential energy; here it is a question of the position of the coils *relative to one another*.

There is a principle fully discussed in books on mechanics and heat called the principle of *Conservation of Energy*, which asserts that *energy is indestructible*: it can be transformed from one condition to another, but like matter it can neither be created nor destroyed. Thus when a stone falls it starts with a certain stock of potential energy; as it descends this gradually disappears, being transformed into kinetic; just before it strikes the ground the energy is all in the kinetic form; and *after* it has struck, this bodily kinetic energy is changed into heat, that is, molecular kinetic energy. A piece of coal possesses potential energy due to *its position relative to the oxygen of the air*—to the fact, that is, that it is separated from the oxygen but is capable of combining chemically with it: such energy may be termed "chemical potential energy." When the coal is burned it combines with the oxygen, and this potential energy is converted into heat. The mechanism of a locomotive enables us to re-convert some of this heat into bodily kinetic energy, as shown in the movement of the train; and lastly, when the brake is put on this is again converted into heat. But throughout all these changes there is neither *creation* nor *destruction* of energy.

¹ The student to whom the subject is new must be careful not to confuse between the word *potential* as here used, and the *electric potential*; no doubt there is a relation between the electric potential and potential energy, but for the present it is best to disregard it.

Energy in whatever form is capable of mathematical measurement in the same way. The unit of work commonly adopted for practical purposes is defined as the work done in lifting a pound-weight through a foot, or (which is the same thing) the work done by a pound-weight in falling through a foot: this unit is called a *foot-pound*. For scientific purposes another unit called an *erg* is often employed; it is difficult to define it in a simple way, but it is practically equal to $\frac{1}{73,756,000}$ of a foot-pound. Another unit called a *joule* is equal to 10,000,000 ergs—i.e., about $\frac{1}{7}$ foot-pound. Still another unit, chiefly used in connection with heat and called a *calorie*, is about 42,000,000 ergs, or 3 foot-pounds.

The work done in lifting W pounds-weight through h feet, or when W lbs. falls through h feet, is clearly Wh foot-pounds.

EXERCISE:—About how many *joules* of work are done by a steam-crane in lifting a block of stone weighing half a ton to a height of 30 feet?

62. Energy of a Freely Charged Conductor. In any process of charging a conductor work has to be done. If it be charged by friction the greater part of the work expended in rubbing is wasted in heating the muscles of the arm, etc.; but a portion is stored up as energy in the conductor, and when the latter is afterwards discharged this store is transformed into heat, although the amount is generally very small. This is the source of the heat of an electric spark. That even a small spark is hot can be shown by briskly rubbing an insulated metal ball with fur and holding it over a gas-burner, when the gas will be ignited.

The energy of a charged conductor is an instance of *potential* energy, and when it is discharged it is transformed into kinetic.

If a charged body be held over light substances these are lifted; the conductor thus does work by virtue of its potential energy.

The energy of a charged conductor may be likened to that of a distended india-rubber air-bag, and just as the latter depends jointly upon the excess of air forced in and its pressure above that of the external air, so the former depends jointly upon the charge and potential, in other words, *is proportioned to their product*.

Care should be taken to avoid the popular error that electricity is itself a form of energy. *Heat*, as explained in treatises on that subject, *really is* energy, but electricity is no more energy than is air or water.

It should also be noticed that all energy is of the same *essential nature* whatever form it takes or whatever its source. Electricity is something utterly different from matter, and potential is something utterly different from mechanical pressure; but the energy of a charged conductor is as truly mechanical as that of a horse. The phrase "electrical energy," sometimes employed, simply refers to the *way in which the energy manifests itself*, not to its nature.

63. Analogy of Potential to Temperature and Level. It is only within the last few years that the conception of potential as electrical pressure has been entertained. Previously one had nothing to go upon but certain dry mathematical definitions, and the potential was apt to remain in the minds of students as a kind of misty abstraction with no physical meaning whatever. Accordingly it has long been the custom to illustrate it by two more or less faulty analogies. The object of these appears to be to enforce the fact that electricity tends to flow from a conductor of high to one of low *potential*, and not necessarily from one of big to one of small *charge*.

1. *Analogy to Temperature.* A hot body is said to have a *high temperature* and a cold one a *low*. By *heat* we mean that influence which when it enters a body makes it hot, that is, raises its temperature, while when it leaves the body the latter becomes cold, that is, its temperature falls. Thus if we pour cold water on the fire, heat passes from the fire to the water, the water becomes heated and boils, while the fire becomes cooled and partly extinguished. The *mere temperature* of a body is no criterion of the quantity of heat in it: thus a thimbleful of boiling water has a higher temperature than a gallon of cold, although the latter may contain more heat. What determines the flow of heat from one body to another is their difference of *temperature*, not the difference in the *amounts of heat* in them: thus if the thimbleful of boiling water be stirred up with the gallon of cold, heat will flow from the former to the latter, despite the fact that the former already contains less heat. In this way it is made out that temperature corresponds to potential, while heat corresponds to electricity. Moreover, when two bodies (*e.g.*, two masses of water) at different temperatures are brought into contact, heat flows from the one of higher temperature to the one of lower until their temperatures are equalised: this corresponds to Poisson's Principle.

2. *Analogy to Level.* Water always tends to flow from a place of high level to one of low. If a vessel containing a pint of water stand on the table, and be connected by a pipe with another on the floor containing a gallon, the former will run into the latter despite the fact that it already contains less. Thus after a fashion level corresponds to potential and water to electricity. Moreover, if two or more vessels containing water at different levels be connected by pipes a flow will take place between them until the water stands at the same level in each, which again corresponds to Poisson's Principle.

The great defect in both these analogies is that they present *nothing whatever to correspond to the dielectric*, which is the essential thing in the electrical action; in this respect they are far inferior to that of the india-rubber air-bags.

In other respects the analogies are apt to mislead; in the second, which is the one most resorted to, the *weight* of the water (which has nothing in electricity corresponding to it) is a frequent source of confusion; on the other hand the analogy lends itself well to the conception of potential-gradients. It is also a very serviceable analogy in connexion with energy for just as the energy of a head of water is proportional to the product of the quantity of water and its height above the ground, so the energy of an electric charge is proportional to the product of the charge and potential.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER III.

1. A freely charged body produces a potential (of the same sign as its own) in the dielectric all round it, which becomes weaker as we recede (§ 46).

2. **POTENTIAL-GRADIENT.** The dielectric *outside* a freely charged conductor is a region of potential-gradient, which in the case of a *positive* charge is a down-gradient as we *recede from* the conductor, and in the case of a negative charge is a down-gradient as we *approach* it (§ 46).

3. The interior of a hollow conductor is a region of *uniform potential*, in other words of *nil-gradient*, however the conductor be charged, always provided there is no electrified body *inside* it (§§ 47, 48), the potential of the entire internal dielectric being equal to that of the conductor itself.

4. Inductive displacement (§ 49).

5. No inductive displacement in a field of uniform potential (§ 50).
6. There is *no charge* on the inner surface of a hollow conductor under whatever circumstances it is placed, provided there be no electrified body *inside* it—but its *potential* inside is the same as outside (§ 51). Principle of *emptying out* (§ 51).
7. When a conductor having a (positive) charge is inside but not touching an insulated hollow conductor, it imparts to the latter an induced potential equal to the free one it would have if the inside conductor were absent and itself possessed the said charge. Also by inductive displacement its outer surface acquires a (positive) charge equal to that on the internal conductor, and its inner an equal (negative) charge (§ 52).
8. Electric screens and shadows (§ 53).
9. Method of testing the amount of charge (§ 55); compare it with the method for testing potential (§ 40).
10. Two freely charged conductors may have the same potential but different charges (or the same charge but different potentials) (§ 56, 57).
11. Specific Inductivity (§ 58).
12. Influence of a neighbouring conductor (§ 59).
13. The electrostatic capacity of a conductor depends upon *its size and shape, the presence of other conductors, especially if earthed, and the specific inductivity of the surrounding dielectric* (§ 60).
14. Work and Energy (§ 61). The energy of a freely charged conductor is proportional to the product of its charge and its potential (§ 62).
15. Analogy of potential to temperature and level (§ 63).

EXERCISES ON CHAPTERS II. and III.

1. An insulated conductor, A, is brought near the cap of a gold-leaf electroscope which has been charged positively. State and explain what will happen (1) if A is unelectrified, (2) if A is charged positively, (3) if it is charged negatively.

Also state and explain what will happen if A be earthed.

2. Describe an experiment whereby you could accurately prove that when one kind of electrification is produced the opposite kind is also produced in equal quantity.

3. An electrified metal ball is introduced into a dry glass tube closed at one end, and then the tube, being held in the hand, is brought near to the cap of an electroscope. What will be the effect on the leaves if the exterior of the tube (1) is, (2) is not, covered with tin-foil?

4. The extremity B of a wire A B is attached to the cap of a gold-leaf electroscope. By means of an insulating handle the other end, A, is placed in contact, first with the blunt and then with the more pointed end of a pear-shaped insulated and electrified conductor. Describe and explain the movement of the leaves of the electroscope.

5. An electroscope is surrounded by a cylinder of wire gauze which is put to earth. If an electrified body is brought near it, how will the leaves behave? Give reasons for your answer.

6. Under what circumstances is it possible to transfer *the whole* of the charge on a conductor to another insulated conductor?

7. Describe an experiment to prove that two points may have the same potential, though one is positively charged and the other is either uncharged or charged negatively.

8. How could you show experimentally that when a charged conductor is introduced into another conductor without touching it the charge induced on the external conductor is equal to the inducing charge?

9. Discuss the analogies between differences of level, temperature, and electrical potential respectively.

10. Two brass spheres, of which one is heated by a lamp while the other is surrounded by melting ice, are connected by a metal rod. If it is desired to make electricity pass from one to the other along the rod in the same direction as that in which the heat flows, describe the nature of the electrical arrangements which would correspond (1) to the lamp, (2) to the ice.

11. Describe how to arrange an experiment so that a conductor charged all over with negative electricity may nevertheless receive a further negative charge on being connected with the ground by a conducting wire.

12. An electrified body is brought into the neighbourhood of (a) an insulated conductor, (b) an earth-connected conductor. Describe exactly the effect on the potentials of the electrified body and of the un electrified conductors in each case.

13. Two equal insulated uncharged metal spheres, B and C, are placed at opposite sides of and at equal distances from a charged sphere A. What is the electrical state of B and of C, and what will happen if the part of B nearest to A is connected by a fine wire with the part of C farthest from A?

14. (1903) The case surrounding the gold leaves of an electroscope is made of metal with glass windows. When the instrument is placed on an insulating stand and the case charged with electricity, is there any divergence of the leaves? When the instrument is placed inside an insulated and charged metal vessel, is there any divergence? Give reasons for your answer.

15. (1899) Two equal conducting spheres are charged, one with positive and the other with an equal quantity of negative electricity, and are placed a certain distance apart. A third conducting sphere, which is insulated but uncharged, is placed exactly half-way between them. What is (i) the potential, (ii) the state of electrification of this last sphere? Give reasons for your answer.

CHAPTER IV.

DISTRIBUTION OF ELECTRICITY ON CONDUCTORS.

64. The Charge resides entirely on the Outer Surface of a Conductor: Biot's Theorem. In § 51 we have seen that in the case of a freely charged hollow pot none of the charge resides on the *inner* surface, and that the same is true even when the pot is under inductive influence, provided there be no charged bodies inside the pot.

Now consider a freely charged *solid* conductor. Does the charge in this case reside on the surface, or does some of it penetrate the conducting material? To answer this question we must resort to experiment.



Fig. 22.

In fig. 22, A is a solid insulated conductor (which may be of any shape), and B and C are two metal covers mounted on insulating handles which fit it exactly, and meet so that when placed over A the whole is practically a solid conductor with its outer surface movable. Now fit

B and C over A and give the whole thing a charge, say by touching B with a charged ball. Then remove the covers B and C and test each by a neutral gold-leaf electroscope: they will be found charged. Again test A by the electroscope: *it will be found perfectly neutral*. Hence the charge was entirely on the outer surface.

The experiment may be varied by charging A *before* placing the covers over it. In this case the charge to begin with is of course on

A, which if tested by a neutral electroscope will make the leaves diverge. If now we put the covers on, and afterwards remove and test, it will be found that A is completely neutral, all its original charge having passed on to the covers. Clearly the only use of the covers in any case is to furnish us with an outer surface which can be removed, so that the exterior and interior may be separately tested: but the *fact* must be the same even when there are no movable covers.

The experiment above described is known as Biot's or Cavendish's experiment. Combining it with the result of § 51, we learn that *in any freely charged conductor, whether solid or hollow, the charge resides entirely on the outside surface*. We shall refer to this result as *Biot's Theorem*.

By a modification of the experiments, Biot's theorem may be shown to be true of induced charges or of the local charges due to inductive displacement, always provided that if the conductor be hollow there must be no charged body inside.

EXERCISES: 1. How would you do it?

2. In electrical experiments it is not unusual to employ balls, etc., made of wood coated with tin-foil, and they act precisely as if they were of metal throughout. Why is this? Would it matter whether the balls were solid or hollow?

It should be observed that Biot's theorem is *not true of insulators* under any circumstances, for if instead of a metal ball and covers we employ ebonite, glass, etc., a charge in general remains on the ball after the covers are removed.

Students generally experience great difficulty in reconciling the fact that the *charge* on a conductor resides exclusively on the outer surface with the fact that its *potential* is the same throughout the entire material: it must, however, be remembered that electrical pressure *primarily applied* to the surface of a conductor is *transmitted* throughout its entire material in much the same way as if we have a vessel of air or water fitted with a piston and apply mechanical pressure to the piston, that pressure is transmitted through the entire mass of air or water.

65. How to Test the Amount of Charge on a given Small Area of a Conductor. Consider now a charged conductor, and let P be a certain point on its surface. Consider a given small area, say

a square centimetre,¹ of its surface immediately round P. On this area there will exist a certain portion of the charge. Now suppose we wish to measure this portion practically. To do so we must have a means of taking it off and examining it separately. This is done



Fig. 23.

by means of a *proof-plane*, which is simply a small thin brass disc (fig. 23) mounted on an ebonite handle. This is placed flat on the

area to be examined; it thus for the moment becomes the outside surface of that portion of the conductor, and by Biot's Theorem the charge originally on the area in question is now on the little piece of brass. We now lift the latter off, being careful not to tilt or drag it, and it carries the charge with it. To test the amount of the charge we adopt the method of § 55. A *very small* tin pot (about 1 inch diameter and 3 inches deep) is placed on the cap of a neutral electroscope and the proof-plane carefully lowered into it: *the amount of divergence of the leaves indicates the amount of charge on the small area of the conductor under examination.*

Theoretically the brass A B should accurately fit the part of the conductor on which it is placed, for otherwise it will slightly alter the shape of the conductor and cause a modified distribution of the charge. As, however, we require to test different parts of the surface some of which may be flatter than others, this is impracticable, and it is usual to make the brass flat. Since it is very small, the fitting will be *very nearly accurate*, and quite good enough for all practical purposes unless it happens that the part of the conductor to be tested is pointed, like fig. 11, in ^A which case a *proof-cone* (fig. 24) must be used: this resembles a proof-plane, ^B except that the brass piece, A B, is a hollow cone made to fit over the pointed portion. Many persons, however, content themselves with a proof-plane for all cases.

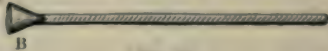


Fig. 24.

66. Distribution of Charge: Surface Density. Now let us take a freely charged conductor of an irregular shape, and by the method

¹ A centimetre is the unit of length in the French or metric system of measurement; it is equal to $\frac{5}{127}$ or very nearly $\frac{2}{5}$ of an inch so that a square centimetre is about $\frac{4}{25}$ of a square inch. The centimetre plays a very important part in many scientific measurements.

of the preceding section compare the charges per given small area at different parts of its surface. A good form of conductor, presenting plenty of variety, is that of fig. 11. If we place the proof-plane on the flattest part of the surface and then carry it to the pot, the leaves of the electroscope will diverge but slightly, if we try the curved part they will diverge more, if we try the aperture they will not diverge at all, while if we try the point (with the proof-*cone*, which of course should have the same area as the plane) they will diverge most of all. Hence we learn that the charge per given small area is greatest round the point, less on the curved part, still less on the flat, and nil inside the aperture—the latter, indeed, being practically the inside of a hollow conductor.

The charge per given small area (generally per square centimetre) immediately round any point on the surface of a conductor is called the *electric density* or *surface density* or briefly the *density* at that point; what we have learned, therefore, is that in a freely charged conductor *the density is greatest at the pointed portions and least at the flat, while if there be any distinct hollows the density in them is nil.*

In the case of a rod the density would be found considerable at and near the ends and very small in the middle; in a flat circular plate it is great at the edges and small in the middle; in a rectangular plate it is great along the edges, greater still at the corners, and small



Fig. 25.

at the middle; and in a sphere it is uniform all over. Fig. 25 exhibits diagrammatically the density at different parts of sundry conductors; the inner continuous line shows the conductor, while the distance of the dotted line from the adjacent points thereof indicates the density at those respective points.

Students are often liable to confuse the results of this section with that of § 44, and to think that because the *density* varies from place to place therefore the potential does so; this is not true,—the potential is of course the same all over, in accordance with Poisson's Principle.

As already seen (cf. §§ 49, 51) we must *not* attribute the potential at a point on the conductor merely to the *local charge* at the point in question.

The conception of electric density and the mode of testing it is precisely the same for induced charges and for the local charges due to inductive displacement as for free charges, but the actual value of the density at any point will in general be different. Thus in a freely charged sphere (not near other conductors and surrounded by nothing but dry air) the density is uniform all over, while when earthed and charged by induction the density is greatest on the side nearest the inducing body, and least on the side directly opposite.

67. Relation between Electric Density and Potential Gradient.

Electric Sparks. In § 51 we have learned that there is no charge on the inner surface of a hollow conductor, and have also seen that this is a consequence of the uniformity of potential, in other words, of the absence of potential-gradient, in the enclosed dielectric. There is in fact an intimate connexion between the electric density *at any point* of a conductor, and the potential-gradient in the dielectric *immediately adjoining that point*, the one being (so long as we keep to the same dielectric) simply proportional to the other. Thus when a conductor of the shape shown in fig. 11 is charged, the potential of the conductor is of course the same throughout, but the potential-gradient of the air immediately surrounding it is steepest at the point, P, and is practically *nil* in the hollow, Q; we may then say that this is the *reason why* the density at P is greatest and at Q least.

From the foregoing principle it will be readily seen that the density at a given point of a conductor having a given charge depends not only on the shape of the conductor but also upon the circum-

stances under which it is placed, especially as respects other conductors adjacent to it. Consider, *e.g.*, a freely charged sphere. If it be surrounded merely by air, which is the condition of things contemplated in fig. 25, the density is uniform all over. But suppose there be placed about an inch from it on one side an earthed metal plate, C D (fig. 26); the potential of the sphere on the right-hand side, B, is the same as on the left, A, but in travelling across the dielectric

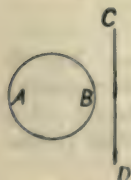


Fig. 26.

to the left we shall have to go one or two feet before we come to a place of zero-potential (§ 46), whereas on the right we strike

zero-potential as soon as we come to the plate: we thus have a much steeper gradient on the right than on the left, and accordingly the electric density is much greater at B than at A.

It will also be seen that the fact of a conductor possessing a sharp point does not *by itself* ensure that the density at that point will be great, because it is quite possible to place the point in such a way that the potential-gradient in the dielectric adjoining it shall be small. For example, if the conductor be a deep metal pot and a pin be soldered on the bottom of it inside, the density at the point of the pin will be nil. Or consider a pear-shaped conductor with a metal plate in front of the point, the two being connected by a wire (as in fig. 27). The portion of the dielectric between the point and the plate may be roughly regarded as the interior of a hollow conductor and therefore (§ 47) the potential-gradient in it is small, so that the density at the point is small—it may in fact if the plate is sufficiently near the point be smaller than at any other part of the conductor.

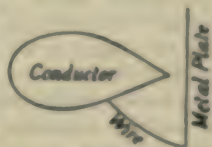


Fig. 27.

When two conductors having a considerable difference of potential are brought near to one another, an electric spark passes between them, the insulation of the intervening air being temporarily broken down, so that they are practically for the moment in electrical communication. The passage of the spark is due to a strain in the air-space between the conductors, and this strain is greater the steeper the potential-gradient in that space. Hence other things being the same, the nearer the conductors are together the more likely is there to be a spark.

EXERCISES:—1. Prove from the principle of this article the truth of the statement at the end of § 66, *viz.*, that when a sphere is earthed and charged by induction, the density is greatest on the side nearest the inducing body, and least on the side directly opposite.



Fig. 28.

2. A charged ball is held inside an earthed metal pot, but not in the middle: is the induced charge uniformly distributed over the interior of the pot? If

not, at which parts is it greatest and which least?

3. A conductor of the shape shown in fig. 28 is freely charged; how is the charge distributed over it?

4. An insulated uncharged metal ball is held near a charged ball at such a distance that no spark passes between them, but on touching the uncharged ball with the finger a spark at once passes. Explain this.

68. Electric Convection from Points. Lightning Conductors. Consider any small area of a charged conductor. The particles of air adjoining that area receive a contact charge and undergo repulsion the amount of which is greater the greater the electric density. Hence at sharp points when the density is very great, the repulsion may become sufficiently strong to overcome the pressure of the air behind the charged particles, in which case the latter will be driven away carrying the charge of the conductor with them : this phenomena is known as *electric convection*, or the *discharging power of points*.

Another closely related action is their *collecting power*. If we take a neutral conductor A with a sharp point, and hold a positively charged conductor B a few inches in front of the point, it is found that A acquires a positive charge just as if there had been actual contact. The explanation is clearly as follows :— B acts inductively on A, and by the principle of inductive displacement the sharp point acquires a negative charge, while the other side of A acquires a positive one. The (negative) density at the point is very great, and negatively charged air particles are carried across to B. Of course these take with them a deficit of electricity, which deficit would otherwise remain on A, so that on the whole A is left with an excess—that is, a positive charge. Moreover the deficit on the air particles is made good by part of the electricity on B, so that the latter loses part of its positive charge, and the final effect is precisely the same as if there had been a direct transference of electricity from B to A.

A *Lightning Conductor* is a device wherein the “collecting power” of points is utilised to help discharge thunder-clouds. It consists of an iron rod run up the side of the building to be protected and insulated from it, its lower end being well imbedded in the ground and its upper terminating above the top of the building in one or more sharp points.

In place of lightning conductors it was proposed by Clerk Maxwell to cover the building with a network of wire connected to the earth so that it might be screened from electric influence in accordance with the principle of § 53.

SUMMARY OF THE MOST IMPORTANT POINTS IN CHAPTER IV.

1. Biot's theorem—*viz.*, that in any conductor whether solid or hollow, the charge resides entirely on the outside surface. But notwithstanding this the *potential* is the same throughout the entire material (§ 64).
2. Use of proof-plane and proof-cone in conjunction with small pot, for testing electric density (§ 65); compare this carefully with the method of § 40 for testing *potential*.
3. The density may be different at different parts of a conductor being in general greatest at points and edges and least at flat portions. But notwithstanding this the *potential* is the same all over (§ 66).
4. The electric density at any point of a conductor is proportional to the potential-gradient in the dielectric immediately adjoining that point (§ 67).
5. Discharging and collecting power of points (§ 68).

EXERCISES ON CHAPTER IV.

1. It is often loosely asserted that "the density on a charged sphere is uniform"; state exactly under what conditions this is true.
2. An orange, into which a sewing needle has been stuck point outwards, is suspended by a dry silk thread. A charged body is brought near it (1) opposite the point of the needle, (2) opposite the side remote from the needle. State and explain the electrical effect in each case.
3. A sharp point attached to a conductor, A, is held near an insulated charged conductor, B. What will be the effect on B if A is (1) insulated, (2) uninsulated.
4. Two gold-leaf electrosopes similar in all respects, except that a needle projects from the cap of one of them, are placed at equal distances from a charged conductor, and the leaves of both diverge. When the conductor is removed, one pair of leaves collapses suddenly, and the other slowly. Explain the difference in their behaviour.
5. A hemispherical metal bowl to which a short metal point is attached is charged with electricity. What difference, if any, in the rate of loss of charge will there be according as the point is fastened to the concave or convex side of the bowl?

6. A flexible conducting thread to the end of which a needle is attached lies at the bottom of an insulated charged iron pail. One end of the thread always remains in contact with the pail, while the needle is lifted out of the pail (without touching it) by a silk thread. Describe and explain any change which takes place in the charge of the pail during this process.

7. Two metal spheres are placed in contact and charged. On testing with the proof-plane it is found that the density in the niche between them is much less than at the far ends. Account for this.

8. A long brass chain lies coiled up on the cap of an electroscope; the instrument is charged, and the leaves diverge. The chain is then gradually pulled out straight by means of an insulating handle, and the divergence of the leaves is observed to become less and less. What does this show?

9. What is the average surface density on a conductor electrified only by inductive displacement?

10. Two spheres of unequal sizes are placed a considerable distance apart and given equal charges. Which has the stronger potential and which the greater electric density?

11. A sphere A surrounded by air is uniformly charged. Another equal sphere B is surrounded by paraffin wax has an equal uniform charge. Is there any difference in (1) the surface densities, (2) the potentials of A and B? Give reasons.

12. (1902.) Two equal metal spheres are placed close together but not in contact. Equal charges of electricity are given to the spheres. Give a sketch showing the general character of the distribution of electricity over the spheres when the charges are (a) of the same sign, (b) of opposite sign.

13. (1901.) A positively charged small body is placed in the neighbourhood of a metal sphere; give diagrams roughly indicating the distribution of electricity over the sphere (1) when the sphere is insulated and uncharged, (2) when it is earthed. Diagrams should be given for two positions of the charged body, one of these being near the sphere and the other a considerable distance away.

CHAPTER V.

ELECTRICAL MACHINES AND CONDENSERS.

69. The Frictional Electrical Machine. A frictional electrical machine is a mechanical arrangement for generating a charge by the friction of two suitable substances, and for collecting and storing the charge so produced. Such a machine comprises essentially three parts: the *generator*, consisting of the body rubbed and the rubbers, the *collecting combs*, and the *prime conductor*, in which the charge collected by the combs accumulates. One of the earliest machines of this type was the *Cylinder Machine*, but as it would never work its proper place is in a museum of useless antiquities. A much better form is the *Plate Machine* shown in fig. 29. The generator consists of a circular plate of glass, or better of ebonite, mounted on an axle which is supported by two upright wooden supports, and is terminated by a handle by means of which the plate can be made to rotate. At the top of the two wooden uprights is a crosspiece under which are fixed by means of clamping screws two rubbers, and a similar pair is attached vertically beneath them to the base of the framework, both pairs being so arranged as to bite the plate so that when the latter revolves it experiences friction and becomes electrified. The best kind of rubbers consist of leather or silk covered pads coated



Fig. 29.

with electric amalgam (§ 21) which give the plate a strong positive charge. The makers of the machines usually attach to the rubbers long silk flaps, which cover two quadrants of the plate, it is, however, a mistake to do this, as the machine works better without them, especially if the plate be of ebonite.

The prime conductor is a thick bent brass rod, usually with one or two knobs attached, it is supported by the framework but insulated therefrom, and to its ends are attached U-shaped brass rods whose inner sides are studded with sharp steel points; these constitute the collecting combs.

The action of the machine is readily understood:—Following a portion of the surface of the plate from the lower pair of rubbers round through a complete revolution we notice that as it leaves the rubber it is positively charged and when it arrives at the right hand comb this charge is transferred to the prime conductor by the “collecting power” (§ 68) of the steel points. After passing the comb it is therefore neutral. It next comes under the influence of the top pair of rubbers when it again receives a positive charge and this in turn is transferred to the prime conductor by the action of left hand comb. And so on. Hence as we continue to rotate the handle, the charge on the prime conductor continually increases until its potential becomes equal to that conferred upon the plate by the friction of the rubbers, after which any further turning of the handle is sheer waste of labour. If the machine be made with an ebonite plate and be clean and dry and the rubbers in good order the prime conductor usually becomes charged as fully as possible by two or three complete turns.

As generally worked the rubbers of the machine are earth-connected, that is, they are not insulated, but directly connected with the framework of the machine. In this way no charge accumulates on the rubbers. If, however, they are insulated, then the negative charge accumulates, and finally becomes sufficiently great to prevent the positive charge produced on the glass from reaching the combs, and thus prematurely the machine ceases to work. If rubber and prime conductor are both insulated, but connected together by a conducting wire, then the negative of the rubber neutralises the positive charge induced in the prime conductor, and, however hard the machine may be worked, no sign of electrification can be detected in either rubber or prime conductor, thus again proving that the quantities of electricity produced by friction are equal, but of opposite sign.

70. The Electrophorus. This is a neat little instrument which can hardly be called a *frictional* machine, because, although friction is necessary to start it, its main action is due to induction. It is shown in fig. 30. It consists essentially of two parts: a circular brass plate B, generally called the *disc*, to which is attached an insulating handle (which ought to be of ebonite, but is generally of glass, on the principle that cheapness is more important than efficiency), and an ebonite plate E, called the *cake* (the ebonite being frequently replaced by some resinous substance on the same principle). The lower side



Fig. 30.

of the cake must be earthed (for a reason into which for elementary purposes it is needless to enter), either by simply resting it on the table, or still better by having it fitted into a shallow earthed metal base called the *sole*. To work the instrument we first beat the cake with fur, which gives it a negative charge and produces a field of negative potential in the air above (§ 46.) We then hold the disc by the insulating handle, and set it on the cake as shown in the diagram; it then partakes of the negative potential of the field, or to put it in other but equivalent words, the negative charge of the cake acts upon it inductively, giving it a negative induced potential.¹

The disc B is now momentarily earthed by touching it with the finger, when electricity runs into it from the earth in sufficient quantity to bring its potential up to zero, so that it acquires a positive charge. The disc is lastly lifted (by the handle), when, the inductive influence of the cake being removed, the positive charge confers upon it a positive potential, and if it be made to touch an

¹ There is practically no *contact* charge conveyed from the cake to the disc. Since the cake is a non-conductor there would be very little even if the two fitted accurately over one another, but as a matter of fact the surface of neither is truly plane, and the contact occurs only at a few points, so that there is a thin layer of air between. The inductive action of the cake takes place through this layer. But that is not all; for the charge on the cake does not lie entirely on the surface, as it would if it were a conductor, but penetrates the interior, and the internal part of the charge acts inductively on the disc across the upper layers of the cake itself.

insulated neutral conductor part of its charge will flow into the same in obedience to Poisson's Principle. Generally a spark passes at the same time. If instead of an insulated conductor we employ an earthed one (*e.g.*, the knuckle) the disc is completely discharged. After discharging it may be replaced on the cake, touched and lifted, and the same thing occurs again. We may thus charge any conductor by instalments, but if the conductor be of large capacity the process is very tedious on account of the small capacity of the disc, and the consequent small charge it acquires each time.

Since, except for the original electrification of the cake the whole process is one of induction, the charging of the disc in no way diminishes the charge on the cake, and were it not for accidental leakage the cake when once electrified would charge the disc an indefinite number of times.

It should be observed that it is not necessary to delay earthing the disc until after it is on the cake: it may be earthed before or simultaneously; in any case the final charge on the disc will be the same. Instead, therefore, of using the finger, we may allow the edge of the disc to touch the flange of the sole in the act of lifting or setting down. Sometimes the instrument is made with a small brass peg through the ebonite cake, its lower end being soldered to the sole and its upper lying flush with the top of the ebonite; this earths the disc at the instant it is put on the cake, and saves time.

71. Limit to the Action of an Electrical Machine. As pointed out in § 69 the action of a frictional machine ceases as soon as its prime conductor attains a certain potential; this is called the *limiting* potential, and it is important to note that *every electrical machine has a limiting potential* whose value depends upon the nature of the machine. A good frictional machine will give a potential up to about 100,000 volts.¹

As soon as a machine has reached its limiting potential, and *all the while it retains that potential*, it is impossible to make it yield any further charge: if, however, we *remove some of the charge from it, so as to weaken its potential*, we can by further working it reinstate the charge so removed: in this sense the action of a machine is unlimited. One of the uses of electric machines is to charge condensers, which are

¹ A volt is the unit of potential; it is seldom mentioned in Electrostatics—it is about equal to the electromotive force of a Daniell cell (§ 136).

essentially conductors of large capacity ; the condenser is connected to the prime conductor of the machine, and the latter then generates sufficient charge to confer the limiting potential upon *both the prime conductor and the condenser*, the amount so generated being of course much greater than if the condenser were absent.

It should be observed that, comparing a good electrical machine with, say, a copper ball beaten with india-rubber, though the machine doubtless affords a stronger potential, this is not its main advantage, which consists rather in the fact *that it supplies a charge rapidly*. To charge a condenser from the machine may be likened to filling a pail from a pump; to charge it from the beaten ball may be compared to filling the pail by ladling water into it with a spoon.

72. Condensers. It frequently happens in electrical experiments that we require a conductor to have a very big charge. Now suppose we are furnished with a good electrical machine, the limiting potential (§ 71) of whose prime conductor is V , and with a conductor A ; by connecting A to the prime conductor of the machine it can be made to acquire a potential equal to V but no greater; it will then have a certain charge, Q , which will be the greatest possible under the given circumstances, the amount of this charge being given (§ 60) by the equation

$$Q = CV$$

where C is the electrostatic capacity of the conductor A .

Now if A be a simple conductor of manageable size, C may be too small to give to Q anything like so great a value as required. If then we are to get the desired charge on our conductor we must have some means of increasing its capacity, in other words, of *weakening the potential produced in it by a given charge*. To effect this we avail ourselves of the principle of § 59: we place the conductor A in the vicinity of an earthed conductor B . Moreover, as we require a very decided weakening of the potential of A , we must bring all parts of B as near to A as possible. Any instrument constructed on this principle is called a *condenser* or (electrostatic) *accumulator*.

Condensers are made of various forms, but they are all essentially the same, consisting of *two metal plates separated by a dielectric*. In the process of charging, one of the plates is kept earthed, and the other which is insulated is connected to an electrical machine or other convenient source. Suppose now that the potential of the insulated plate becomes V , then if C denote its capacity in presence of the earth

plate (usually for shortness called the *capacity of the condenser*), and Q the charge on it (usually called the *charge in the condenser*), Q is given by the equation

$$Q = C V.$$

As soon as V becomes equal to the limiting potential of the machine, Q is as great as possible, and the condenser is said to be fully charged.

It is important to note the condition of the earth-plate after charging; its *potential* is of course zero, while it has an induced *charge* of the opposite sign to that on the insulated plate. The amount of this induced charge is in general somewhat less than Q , but in all the practical forms of condenser in which the two plates are very close together, *their charges are to all intents and purposes equal*.

73. The Leyden Jar. This is one of the most convenient forms of condenser. It is shown in fig. 31. It consists of a wide-mouthed glass jar the sides and bottom of which are coated both inside and outside to within a short distance of the neck with tin-foil. The mouth is fitted with a bung of "baked" wood, which is a fairly good insulator; and through this passes a brass rod which touches the inner tin-foil coat at the bottom of the jar, and on the top of which is fixed a brass knob.

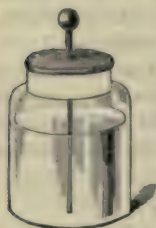


Fig. 31.

It is usual to varnish the glass above the tin-foil both inside and outside with shellac varnish in order to improve the surface insulation, but besides this it is essential that the glass itself should be good insulating glass free from lead, otherwise the jar is practically useless. Provided the insulation afforded by the glass be good it does not much matter about the bung; there is, however, a practical objection to the bungs commonly used—viz., that it is necessary in some experiments to turn the jar upside down or to connect several together by wires, etc.; and as the bungs generally do not fit at all tight, this is very awkward. An india-rubber bung is on this account far preferable to a wooden one.

74. Charging the Leyden Jar. The ordinary method of charging the jar is simply to stand it on the table and place its knob against the prime conductor of an electrical machine; the outer coat then constitutes the earth plate and the inner the insulated, and supposing the machine to yield a positive charge, the effect is to give the

inner coat a certain positive charge and the outer a practically equal (§ 72) negative charge : also the inner coat acquires a certain positive potential while the outer remains at zero potential. In order that the jar may be fully charged its knob should be placed in *actual contact* with the prime conductor without any air gap, which ensures that the potentials of the inner coat and prime conductor are *equal* (Poisson's Principle), and the machine should be worked sufficiently to ensure its attaining its *limiting potential*.

We may also charge the jar by the "inverted" method which, however, is somewhat awkward ; it consists in earthing the knob say by holding it in the hand and placing the outer coat against the prime conductor of the machine, in this way the insulated and earthed coats are reversed and supposing the machine to yield a positive charge the outer coat will become charged positively and the inner negatively. After charging in this way care must be taken not to set the jar on the table while holding the knob : the reason for this and the proper course to pursue will appear in the next article (§ 75).

It is important to note that it is impossible to charge a Leyden jar effectively if, *during the process*, we keep the coat not in contact with the machine *insulated*. The reason has been anticipated in the last paragraph of § 59 ; the latter coat being very thin exerts no weakening effect on the potential which a given charge produces in the other, so that its capacity is not increased—in short the jar is not a condenser at all. Thus if we set a jar on an insulating stool and place its knob against the prime conductor of the machine, no matter how vigorously the latter be worked the inner coat will receive *merely the same small charge as it would do if the outer had no existence*. It is sometimes said that we cannot in this way charge the jar at all, but this is hardly true ; we can charge the inner coat as an isolated conductor, but we cannot charge the jar as a condenser.

Of course, *after* the jar has been charged in the ordinary way with its outer coat earthed, we may insulate the latter without in any way altering the state of the jar.

EXERCISES:—1. A Leyden jar is placed on an insulating stool and its knob connected with the prime conductor of an electrical machine. The machine is then worked a little and the finger afterwards brought near the outer coat of the jar when a spark passes : explain this. Show also that if these operations were repeated a great number of times the jar would become properly charged.

2. The inner coating of a Leyden jar is connected by a wire with the prime conductor of an electrical machine and also with a gold-leaf electroscope. If the jar rests upon a sheet of glass, a quarter of a turn of the machine produces a large divergence of the leaves of the electroscope. If the glass be removed ten turns of the handle are required to produce the same deflection, Explain this.

75. Discharging the Leyden Jar. If after a jar has been charged *we establish conducting communication between the two coats,* their charges, which we have already seen to be equal and opposite, neutralise one another, the potential of each becomes zero, and the jar is discharged. A convenient way of establishing such communication is by means of a *discharging-tongs* (fig. 32) which is simply a pair of brass rods terminating in brass knobs and working stiffly on a pivot, the whole being mounted on a glass or ebonite handle: the pivot-joint permits of the knobs being placed at a convenient distance for reaching the knob and outer coat of the jar. Suppose now we have charged our jar in the ordinary way, and have it standing on the table. To discharge it we *hold the tongs by the insulating handle*, make one knob touch the outer coat and then approach the other to the knob of the jar, when, at a certain distance a bright spark passes with a sharp click; this *nearly* discharges the jar—to complete the discharge we bring the knobs into actual contact. Or, if we please, we may first make one knob of the tongs touch the knob of the jar and then approach the other to its outer coat—the only difference is that in this the spark passes between the knob of the tongs and the outer coat.



Fig. 32.

If we *hold the tongs by the brass portion and touch the earthed coat of the jar first* we get precisely the same effect as if we held them by the insulating handle, but if we touch the insulated coat first we *at once* establish conducting communication between the two coats *via* the tongs, body, floor, and table, so that the jar discharges itself prematurely; it does not, however, under these conditions usually produce a spark so much as a kind of “fizz,” the reason being that the opposite charges on the coats have to pass through considerable resistance before meeting one another so that the action takes place more slowly.

If after charging a jar by the “inverted” method (§ 74) we set it on the table while still holding the knob, we obtain premature dis-

charge in the manner just explained; to obviate this we first set it on an insulating stand, then leave hold of the knob, and finally lift it on to the table by its outer coat.

If one coat of a charged jar be brought into contact with one hand and one with the other so that the jar discharges itself through the body, it produces an unpleasant sensation or "shock" which if the charge be large may be very dangerous. If other resistance be interposed in the circuit the shock may still be experienced though in a less severe form—this often happens during the premature discharge of the jar above considered.

EXERCISES:—1. A Leyden jar is charged in the ordinary way and then discharged by means of insulated tongs. Will it make any difference in the ultimate state of the jar whether it be standing on the table or on an insulating stool, and if so, what difference?

2. A Leyden jar is charged in the ordinary way and then stood on an insulating support. It is then discharged by *uninsulated* tongs. Will it in any way matter whether the knob on the outer coat be touched first?

3. A charged Leyden jar stands on the table, and a person stands on an insulating stool placed on the floor. Will it be dangerous for him to touch the knob of the jar?

4. How would you prove experimentally the truth of the statement made in § 74, *viz.*, that it is impossible to charge a Leyden jar when both coats are insulated?

76. Piecemeal Discharge. When we establish conducting communication between the two coats of a charged Leyden jar, the jar is discharged all at once. But we may discharge it in small quantities at a time as follows:—

Place the jar (after having charged it in the ordinary way) on an insulating stand. Touch the knob, we get a *feeble* spark with no appreciable shock; then remove the finger from the knob and touch the outer coat, we get another feeble spark; then take the finger away from the outer coat and again touch the knob, we get another feeble spark, and so on. This process is generally termed *discharging by alternate contacts*; it requires a very large number of such contacts to effect a complete discharge. To explain the process, let us suppose the charge on the inner coat to be positive, then the induced charge on the outer will be negative. When the jar is first placed on the insulating stand, the potential of its inner coat is positive, and that of its outer is zero. We now touch the knob: this reduces the potential of the inner coat to zero, and sufficient electricity escapes to the earth to allow of this happening. The inner coat

is therefore partly discharged, a spark occurring in the act. But the amount of electricity which escapes to earth on touching the knob is *only a minute fraction of the charge on the inner coat*, for this reason:—The outer coat has a big negative charge, and the tendency of this is to produce by inductive action across the dielectric a very low (that is, a strong negative) induced potential on the inner; but the latter is really at potential zero, hence a big positive charge must *remain on* it in order to neutralise the negative (induced) potential, so that only very little escapes. Then again as to the spark from the outer coat:—Before the knob is touched the potential of the outer coat is zero, the negative charge thereon being *just* sufficient to neutralise the positive potential which it would otherwise possess arising from the inductive action of the inner coat across the glass. When part of the charge is removed from the inner coat by touching the knob, this inductive action is lessened, and the negative charge on the outer coat is *more than* sufficient to effect the said neutralisation, so that *the potential of the outer coat becomes negative*; accordingly, on now touching the latter, electricity runs into it from the earth in sufficient quantity to bring its potential up to zero, or in other words, part of its negative charge escapes to earth, this being as before quite small and accompanied by only a feeble spark. The removal of this negative charge again renders the potential of the inner coat positive, so that the next contact with the knob gives another spark, and so on; a small positive charge being removed from the inner and a small negative from the outer at every contact, until the discharge is—if one has the patience to go on—complete.

EXERCISE (1903):—A Leyden jar, charged in the ordinary way, is placed on an insulating stand. What effect is experienced by a person touching the knob of the jar? Explain why the jar is not entirely discharged by the contact.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER V.

1. Description and action of frictional machines (§ 69).
2. Description and action of electrophorus (§ 70).
3. Limiting potential of an electrical machine (§ 71).
4. General principles of condensers (§ 72).
5. Charging and discharging the Leyden jar (§§ 74, 75, 76).

EXERCISES ON CHAPTER V.

1. How do you explain the fact that in the ordinary process of charging a Leyden jar it is necessary to connect its outer coating to earth?

2. A sheet of tin-foil is suspended by a dry silk thread and charged as highly as possible by an electrical machine, but on discharging it only a slight spark is obtained. If the tin-foil is placed on a sheet of dry glass lying on the table and charged by the same machine a bright spark can be obtained. Explain the cause of the difference.

3. If a Leyden jar, A, stand on an insulating stool, and its knob be connected to the prime conductor of an electrical machine, it cannot be charged. But if, standing on the stool, its outer coat be connected to the knob of another jar, B, whose outer coat is earthed, then on working the machine both A and B become charged. Explain this.

4. Two Leyden jars of different sizes have the outer coatings earthed, and *equal charges* are given to the inner ones. Their knobs are now connected by discharging tongs, and a spark is observed to pass. Explain this.

5. An electrical machine is placed inside an insulated chamber lined with tin-foil. The rubber of the machine is connected with the tin foil. What will be the effect upon an electroscope placed outside and connected with the chamber when the machine is in action? Explain your answer.

6. The plate of an ebonite electrophorus is rubbed with flannel, and the metal cover put on but not touched. Is the potential of the cover positive or negative with respect to the earth? How would you find out by experiment.

7. (1901.) A Leyden jar is connected to the positive terminal of an electrical machine, the outer coating of the jar being to earth. When charged it is disconnected and placed on an insulating stand. The inner coating is then put to earth and the outer coating is touched with the knob of an equal jar held in the hand. Will the second jar be charged, and if so with what kind of electricity?

8. Explain the action of the points on the prime conductor of an electrical machine. What experimental result can you quote in favour of your explanation?

PART II.

MAGNETISM.

CHAPTER I.

GENERAL PHENOMENA.

77. Natural and Artificial Magnets. The name *Magnet* was applied at a very early date to pieces of a mineral found at Magnesia in Asia Minor. This substance, now known as *Magnetite* or *Magnetic*

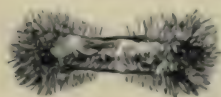


Fig. 33.

iron ore (Fe_3O_4) or *lodestone*, was found to possess the property of attracting iron and steel; thus if a piece of it be dipped in iron filings the latter will adhere to it, more especially round the ends (fig. 33).

A lump or strip of magnetite constitutes a *natural magnet*. In practice such are rarely used, because very much better ones can be made by artificial

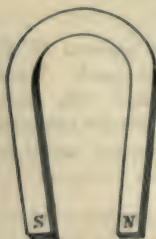


Fig. 35.

means. Artificial magnets are bars of steel or iron which

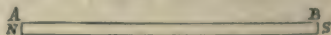


Fig. 34.

have been treated in certain ways of which we shall learn later; they are sometimes straight (fig. 34), when they are called *bar magnets*; and sometimes are bent round so that their ends come near together, when they are called *horseshoe magnets* (fig. 35). In our experiments we shall generally suppose artificial magnets employed; natural ones possess, however, just the same properties, but as a rule much weaker.

78. Magnets and Magnetic Substances. Any substance capable of conversion into a magnet (whether it actually is one or not) is said

to be a *magnetic substance*, and when we so convert it we are said to *magnetise* it. Thus, ordinary iron and steel are magnetic substances, but it is not until after certain treatment that they become magnets. The only other distinctly magnetic substances are the metals cobalt, nickel, manganese, and chromium, but their magnetic powers are somewhat feeble compared with iron and steel, and they are seldom used. Iron or steel in its ordinary or unmagnetised state is said to be *neutral*.

79. Test of Magnetisation. Two pieces of neutral iron or steel do not attract one another, but if one of them be magnetised it attracts the neutral one. At the same time (§ 3) the neutral one attracts the magnetised one. Hence, to test whether a body is magnetised or not we must see whether it attracts a piece of *neutral* iron or steel¹; if so it is a magnet, otherwise it is not. A simple plan is to dip the body into iron filings and see if they adhere.

It should be observed that a magnet will attract *magnetic substances only*; it has no action on brass, wood, paper, etc.

80. Magnetic Poles and Polarity. If a bar magnet be suspended in a stirrup so as to be free to turn horizontally, it will come to rest with its ends pointing (approximately) north and south. If disturbed from this position, it will go back to it. If the end that is pointing north be turned so as to point south it will not stop there, but will go back to the north again. The two ends, therefore, have distinct properties. They are called *poles*; the end pointing north is called the *north pole*, and the one pointing south the *south pole*. For a reason which will appear in § 120 some confusion has arisen with regard to these terms, and some writers call the end that points to the north the *south pole*. Others prefer to drop these terms altogether and speak of the end that points to the north as the *north-seeking* pole. Throughout this book we shall follow the usual custom of British writers and use the term *north pole* to denote the pole that *points to the north*.

It will be observed that we have defined the poles of a magnet with a certain degree of vagueness as its "ends," and have not located them as definite points. We shall refer to this again in §§ 88, 119. Meanwhile the student should be cautioned against a definition

¹ A more elaborate method of testing by means of a magnetic needle will be given in § 82.

sometimes met with—viz. that “the poles of a magnet are two points near its ends at which the magnetic force is concentrated”; this is altogether misleading—there are in general *no such points*.

In order to distinguish at a glance between the poles of a magnet, a common practice is to paint the north pole red and the south blue.

Another convenient plan is to have sharp points about $\frac{1}{8}$ of an inch long fixed near each end, on which bits of painted cork or pith can be temporarily stuck; the latter contrivance is especially convenient for magnetic needles (see below).

As it is awkward to suspend bar magnets in stirrups and get them

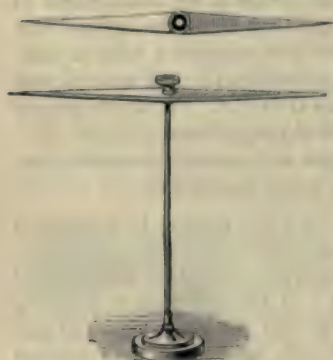


Fig. 36.

to come quickly to rest, it is usual for this purpose to employ *magnetic needles*. These are small magnets (fig. 36) fitted with a brass or agate cup at the centre which can rest on a fine pivot; the needle then quickly sets north and south.

Magnetic needles are sometimes mounted so as to turn in a vertical plane; those turning in a horizontal plane, as in fig. 36 (by far the most usual arrangement), are generally called *compass needles*.

The property of magnets shown in the possession of distinct poles is called *polarity*; we shall frequently employ this term and shall speak of the *north* pole as having *northern* polarity, and the *south* pole *southern* polarity.

EXERCISE :—How would you exhibit the polarity of a horseshoe magnet?

The properties of magnets were at one time accounted for by supposing them to possess some mysterious fluid called *Magnetism*,¹ and there was conceived to be more of this at the poles than elsewhere. There is, however, no reason to believe that there is any “Magnetism” existing as an actual entity in the same sense that electricity exists; it appears rather to be a property inherent in the

¹ Really *two* fluids were imagined: one corresponding to northern and one to southern polarity. But except as a matter of history the whole idea is of no consequence,—it is now quite abandoned.

molecules of the magnetic substance, but manifested only under suitable conditions (§§ 80, 91). The influence of this property is transmitted to another magnetic substance across the air, or other intervening medium, in some way not fully understood, and of which for elementary purposes nothing need be said.

81. Magnetic Attraction and Repulsion. Action of the Earth.

Take a bar magnet or a magnetic needle, A, suspend it so that it can turn horizontally, wait till it comes to rest, and then mark the poles, say, by putting a red pith ball on the north pole and a blue one on the south (§ 80). Set this magnet aside with the markers on it; then take another magnet, B, and treat it in the same way. Now, keeping either one of the magnets, say B, suspended, bring the north pole of A gradually near the north pole of B: we get *repulsion*. After B has come to rest, do the same with their south poles: again we get *repulsion*. Now (B having again come to rest) bring the north pole of A gradually near the south pole of B: we get *attraction*; and the same happens if we use the south of A and the north of B. Hence we have the following law: *Like poles repel and unlike attract*. This is the fundamental law of magnetic action; it plays a considerably more important part in the study of the subject than the analogous law in electrostatics (§ 18).

With regard to the fact that a magnetic needle tends to set north and south, a preliminary note should here be made of what will receive detailed attention in Chapter IV.—*viz.*, that *the earth itself behaves as a magnet*: its northern regions attract the north pole and its southern the south pole of the needle. It is really the force exerted by the earth pulling one pole northwards and the other southwards that is the cause of the needle pointing in these directions.

82. Test for Polarity. Suppose now we have a steel (or iron) bar A B, and we wish to examine its magnetic condition, that is, to determine whether it is magnetised at all and if so which end is a north pole and which a south. We proceed thus:—Set a compass needle on a pivot and bring one end A of the bar gradually towards the north pole of the needle; if we get *repulsion* then A is the north pole of the bar. We then bring the end B in like manner towards the south pole of the needle, when repulsion indicates that B is the south pole. But suppose A had *attracted* the north pole of the needle, then so far as we can tell A may be a south pole, or it may be

neutral; for we have seen (§ 79) that neutral iron attracts a magnet;¹ we must therefore go a step further and bring the *same end A* of the bar towards the *south* pole of the needle; if now we get *repulsion* A is a south pole, but if we *still get attraction* A is neutral. We can then examine B in like manner. *The point always to bear in mind is that repulsion is a sure test of polarity but attraction is not.* It is a common practice to dip the bar into iron filings (§ 79) prior to these experiments, so as to know beforehand whether it is magnetised or not; if the latter we need go no further, while if the former, then since neutrality is excluded the attraction of an end by the north (or south) pole of the needle proves that end to be a south (or north) pole; it is, however, important in any case to bring the bar gradually towards the needle from a distance, otherwise confusion might arise, from induction (see § 87).

83. Magnetic Induction. If a pole of a magnet be brought near

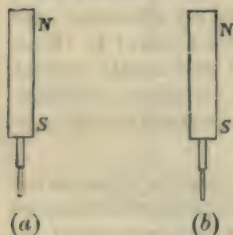


Fig. 37.

fig. 37). If the upper piece be now gently detached from the magnet the lower will still cling to it, and if the two pieces be separately tested by the method of § 82 each will be found to be a magnet with poles as shown (c, fig. 37).

If the experiment be modified, as indicated in fig. 38, by not allow-

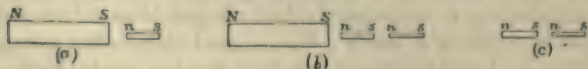


Fig. 38.

ing the magnet and pieces of steel to come into actual contact, these

¹ As will be explained in § 85, the iron is not neutral *while near the magnet*, but it may have been originally neutral, and it is *original state* that we are concerned with.

results will be precisely the same, except that the pieces are not *so strongly* magnetised.

The production of a magnet, as in these experiments by the influence of another magnet (either with or without actual contact), is called magnetisation by *induction*, and the phenomenon in general is termed *Magnetic induction*.

84. Differences in the Magnetic Behaviour of Iron and Steel. Permanent and Electro Magnets. Most people know that steel and iron are not exactly the same: steel is in general harder than iron; thus while the latter can be easily filed or turned in a lathe it is much more difficult to do so to the former. Different varieties of steel differ greatly in hardness: "mild" steel is nearly as soft as iron, "hard" steel is very hard indeed, "medium" steel is intermediate. In general if a steel bar be made hot and then *suddenly* cooled it becomes harder, while if made hot and *gradually* cooled it becomes softer. An ordinary knitting needle is of medium steel; it can be filed with moderate difficulty, is tough, and requires considerable force to bend it; if it be made red-hot and quenched in water it becomes very hard and brittle, is scarcely touched by the file, and can be snapped into pieces by the fingers. If a needle thus hardened be again made red-hot and buried in hot ashes so as to cool very slowly it becomes so soft as to be very readily filed, and can be bent like a piece of copper wire.

Different specimens of *iron* also differ much in hardness. Cast iron is harder and more brittle than wrought. Generally in magnetism when "iron" is spoken of, good "soft" or "annealed" iron is understood.

Now, although both iron and steel are magnetic substances they differ magnetically in two important respects. We shall first *state* these, and then describe experiments illustrating them:—

1. Iron is more readily magnetised than steel.
2. Steel when it *is* magnetised retains its magnetic properties much better than iron.

Both these points of difference may be shown thus:—Set up two strong bar magnets vertically, and have ready a dozen or so little bars of steel (*c*, fig. 37) and the same number of iron. To one of the magnets attach the steel bars one under another (*b*, fig. 37), and see how many will hang on; there will probably be only two, the

magnetic strength of the second bar being too feeble to support a third. To the other magnet attach the iron bars : probably six or eight will hang on. This proves the first of the foregoing statements.

Next very carefully detach the upper steel bar from the magnet and carry it away, then, as already seen (c, fig. 37) each *retains its magnetism*.¹ Do the same with the upper iron bar ; all the rest will fall off, and when separately tested, as in § 82, will be found neutral. This proves the second statement.

The remarks of this section apply not only to magnetism *by induction* but by all methods, *e.g.*, by the electric current (§ 168).

The details depend a great deal upon the hardness of the steel ; if very hard only one piece can be supported, if medium two or three, if mild more. In any case the piece in contact with the magnet becomes more strongly magnetised the softer it is, but if kept for some months the harder specimens would retain their magnetism best.

It is worthy of special note as a point of importance to the electrical engineer that there is a *particular variety* of steel known as "cast dynamo-steel," now largely employed, which can be magnetised with as great, or even greater readiness than the best wrought iron. On the other hand, the so-called "manganese-steel" is practically non-magnetic.

It is usual to classify magnets as *permanent* or *temporary*. Permanent magnets are those which retain their magnetism when the original magnetising influence is removed ; the simplest forms are the ordinary bar and horseshoe magnets. They must be made of *steel* of a suitable degree of hardness, or, as it is technically expressed, suitably *tempered*. Temporary magnets are those which are magnets only by virtue of some external influence then and there acting upon them, and which lose their magnetic properties as soon as that influence is removed ; thus a soft iron bar touching a pole of a permanent magnet is a temporary magnet. The most important members of this class are *electro-magnets* ; they consist of soft iron bars technically termed *cores*, wound round with copper wire through which an electric current can be passed ; the current makes the core

¹ A body is frequently said to "retain its magnetism" or to "lose its magnetism." The phrases are relics of the now discarded fluid theory (§ 80) ; they are, however, convenient, and do no harm provided we regard the word "magnetism" as a mere abbreviation for "magnetic properties."

into a very powerful magnet, but when the current is switched off the core loses its magnetic properties.¹

Electro-magnets will be more fully considered in connection with Voltaic electricity (Part III., chap. V.).

85. Polarity due to Induction. Referring to figs. 37 and 38 it will be seen that the *south* pole (S) of the bar magnet has been used, and that the end of each of the little bars nearest to it has become a *north* pole. This is, of course, proved by actually testing with the magnetic needle (§ 82). If the *north* pole (N) had been employed the ends nearest it would have been *south* poles. We thus have the following law, known as the "law of induced polarity": *When a bar is magnetised by induction the end of it nearest the inducing pole acquires polarity of the opposite kind.* The student should note this very carefully; it may equally well be expressed by saying that the end *farthest* from the inducing pole acquires polarity of the *same* kind.

This law is equally true of iron and steel. But in the case of the former it is somewhat more troublesome to prove it, because the bars when detached from the magnet lose their polarity altogether. The following experiment, however, meets the case (fig. 39):—

Set a bar magnet vertically as shown, and near it suspend a light iron bar, A B, from a point, O, by means of a thread and a brass stirrup, S. Bring the north pole of another bar magnet gradually towards B (§ 82); it will be repelled, B is therefore a *north pole*. Then bring the south pole of the magnet towards A; it is repelled, and is therefore a *south pole*.

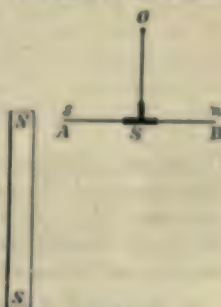


Fig. 39.

EXERCISE:—In the preceding experiment, instead of using the bar magnet, N S, a horseshoe magnet is placed with the north and south poles under B and A respectively. What will be the magnetic condition of A B?

86. Why Neutral Bodies are Attracted. In fig. 38 (a) let *n s* represent a piece of originally neutral iron or steel; the magnet N S acts inductively upon it as shown. By the law of § 81, S attracts *n* and repels *s*. But *n* is a good bit nearer than *s*, consequently the

¹ Unless under special circumstances (§ 97).

attractive force exceeds the repulsive, and *on the whole the little bar is attracted by S*. This explains the apparent attraction of neutral bodies; they are really not neutral, but are magnetised by induction. The fact is often expressed thus: *induction precedes attraction*, or *induction is the cause of attraction*.

Strictly speaking, we should take account of the influence of the other pole (N), both as respects inductive action and force exerted on the little bar; but on account of the relatively great distance of N, its effects are small, and are usually neglected.

EXERCISE :—Will N on the whole increase or diminish the attraction on the little bar?

It should be carefully noted that inasmuch as attraction (in the case of otherwise neutral bodies) is the consequence of inductive magnetisation, and iron is magnetised more readily than steel (§ 84), a given magnet attracts iron with considerably greater force than steel. A hard steel ball clinging to the pole of a magnet can be pulled off with very little force, while a comparatively large force is

required to pull off a similar ball of soft iron. The difference is also well shown by arranging a piece of soft iron and a piece of hard steel on each side of the pole of a compass-needle, as shown in fig. 40.

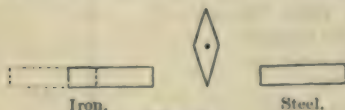


Fig. 40.

If the iron and steel be placed at equal distances from the pole the attraction of the former will be greater, and the pole will be deflected towards it; by removing the iron to a greater distance, as shown by the dotted outline, the two forces may be made equal; they will then balance, and the needle will go back to its natural position.

87. Reversal of Polarity by Induction. Not only does induction magnetise a bar originally neutral, but it may reverse the polarity of one already magnetised. Thus, in fig. 38 (a) suppose the little bar to have been originally a magnet, with the end nearest S a south pole, then the inductive action of N S tends to make it a north pole, and if strong enough will reverse the previous polarity; in fact, this frequently happens in practice when weak magnets are allowed to touch strong ones.

We can now see why it is necessary in the experiments of § 82 to bring the end of the bar under examination *gradually near to the pole of the*

needle from a distance. For suppose the pole of the needle to be a S one, and suppose that the end of A of the bar approaching it is also S, then the pole of the needle will, by induction, tend to make A *north*, and if the induction be strong enough the inductive action will reverse A's original state, and there will be *attraction* which might lead us to infer that A was originally S. But by bringing it up gradually we can generally catch the repulsive action before induction becomes strong enough to reverse the original polarity. Of course, repulsion is always perfectly reliable; the danger is that we may lose the chance of getting it through too great hurry. In the same way, provided we have already ascertained that the body under examination is not neutral, attraction is reliable if it is *genuine* and not due to reversed polarity.

88. Distribution of Polarity in Magnets. Lateral and Terminal Polarity. Simple Magnet. If an ordinary bar or horseshoe magnet be dipped into iron filings, and then taken out and gently shaken, most filings will be found adhering round the ends, and fewer and fewer as we approach the middle, where there are none at all. Again, if we test different parts of the magnet by presenting them in turn to a compass-needle, as in § 82, we find in travelling from the north pole to the middle, all the parts repel the *north* pole of the needle with a gradually diminishing force; in travelling from the south pole to the middle, all the parts repel the *south* pole of the needle with gradually diminishing force, while at the middle neither pole is repelled.

We thus learn that the polarity of the magnet is not confined to the poles, but is *distributed in a varying degree all over its surface*. The polarity along the sides of the magnet is termed *lateral polarity*, that at the ends being sometimes, for distinction, called *terminal polarity*.

Fig. 41 shows graphically the distribution of lateral polarity in an ordinary bar magnet. N S represents the magnet, and at a number of points taken at equal distances along its length perpendiculars are erected proportional to the strength of the polarity at that point. If the perpendiculars are drawn to the

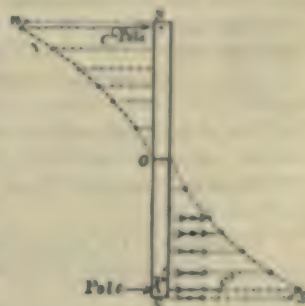


Fig. 41.

left of the magnet for northern polarity and to the right for southern, then the curve, *n o s*, drawn through their extremities gives the desired graphic representation. It clearly shows the gradual weakening of polarity from either pole to the middle; the latter region when the polarity is *nil* is sometimes called the magnetic equator (see, however, § 93).

The polarity at any point of a magnet is frequently said to be due to the *free magnetism* at that point. The phrase is a relic of the old fluid theory (§ 80), but is sometimes convenient. Thus the above curve is said to indicate the *distribution of free magnetism*.

If instead of an ordinary magnet which is of considerable thickness we examine a thin one, such as a magnetised knitting-needle, it is found that there is but slight polarity along the sides, though that at the ends may be strong, and also that the thinner it is the less is its lateral polarity, so that if we could make it *indefinitely* thin, its polarity would be entirely concentrated at its ends. An indefinitely thin magnet (whether straight or not) is called a *simple magnet*, and is the only kind of magnet that really possesses point-poles (cf. § 80); a *thin* needle, if properly magnetised, is a sufficiently close approximation to it for practical purposes.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER I.

1. Distinction between magnets and magnetic substances (§ 78).
2. Poles and polarity (§ 80). The pole that points *to the north* is called the *north pole*.
3. *Like poles repel and unlike attract* (§ 81). *The earth behaves as a magnet*.
4. Use of compass-needle to test polarity (§ 82); *repulsion is always reliable*, but attraction is not.
5. Magnetic induction (§ 83), and the law of the polarity thereby produced (§ 85).
6. Differences in the magnetic behaviour of iron and steel (§ 84).
7. *Induction precedes attraction* (§ 86). Reversal of polarity by induction (§ 87).
8. The polarity of a magnet is in general not confined to its poles, but distributed in a varying degree over its surface. Terminal and lateral polarity: The only case where lateral polarity is entirely absent is that of a *simple magnet*, which has *true point-poles* (§ 88).

EXERCISES ON CHAPTER I.

1. You are doubtful whether a steel rod is neutral or slightly magnetised; how could you find out by trying its action upon a compass needle?

2. What is the magnetic condition of a bar of soft iron held horizontally above and parallel to a bar magnet of the same size resting horizontally on a table?

3. A bar magnet is laid on a table with its N end projecting over the edge. A soft iron ball clings to the under side of the projecting end. State and explain what happens when the S pole of a second bar magnet is brought above and near the N pole of the first?

4. Supposing the first magnet and ball arranged as in the preceding question, state and explain what happens: (1) When the N pole of another magnet is placed underneath the ball a little way from it, (2) When the S pole of another magnet is ditto.

5. If a compass needle is deflected when a steel bar is brought near it how can you find out whether the deflexion is due to magnetism already possessed by the bar, or to the bar becoming magnetised by the compass-needle at the time of the experiment?

6. A compass-needle and a straight strip of soft iron of the same length are fastened together so as to be in contact at both ends. Will the force tending to make the combination point north or south be the same as that which would act on the compass-needle alone? Give reasons.

7. Two bars of soft iron are so placed to the east and west of the north pole of a compass-needle, that the latter still points N and S. If the iron to the E of the needle be replaced by a bar of hard steel of exactly the same size and shape as itself, will the direction in which the needle points be altered? If so, in which direction will it move, and why?

8. A compass-needle is deflected by a bar magnet placed some distance away from it. How is the deflection modified (if at all) when a bar of soft iron is placed parallel to, but not touching, the magnet?

9. A vertical steel rod, of which a portion of length less than half that of the rod is stuck into the earth, is found to be rather strongly magnetised. If you were given a compass-needle and a foot-rule, how could you without disturbing the rod form an estimate of the length of the buried portion?

10. One pole of a magnet made of soft iron and only weakly magnetised is found to be repelled by the north pole of a strong magnet when the latter is some distance away but to be attracted when the magnets are brought close together. Explain this.

CHAPTER II.

NATURE OF MAGNETISM.

89. Magnetism a Molecular Property. Fundamental Experiment. We have already (§ 80) pointed out that magnetism, unlike an electrical charge, is not something which can be put on or taken off a body, but is to be regarded as a property inherent in the molecules of iron and steel and that magnetisation simply consists in so treating these substances that this property shall manifest itself. Why it does not do so under ordinary circumstances, and what is done to the molecules in the process of magnetisation to make it do so, will appear in due course. If we take a thin magnetised steel

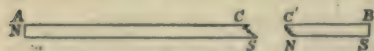


Fig. 42.

bar (a knitting-needle is very convenient), as A B (fig. 42), and break it at any place C, we shall find on testing, as in § 82, that each part, A C, C' B, is itself a complete magnet. A and B being the original north and south poles respectively, will remain so, while C will be found to be a south pole and C' a north. Further, if either of the bits be broken again the same thing will be found to be the case, and so on, no matter into how small pieces the original magnet be divided. It is even possible to grind a magnet to powder, and still each fragment is a magnet, as is proved by the fact that the powder is attracted by *neutral* iron. It is, moreover, impossible by any known means to obtain a piece of substance containing one *kind of polarity only*. It is thus clear that magnetism is a molecular property :¹ the only question is, what is the difference between a magnetised and an

¹ Of course the particles of powder, however fine, are not actual molecules, but there can be no reasonable doubt that if we could obtain the molecules separately they would be found to be magnets.

unmagnetised bar! Does the process of magnetising confer the property on the molecules, or does it merely turn them into positions favourable to its manifestation? We shall see as we proceed that there is every reason for accepting the latter as the true explanation.

90. Magnetic Chains. Take two bar magnets of the same size and strength, and place them together as in fig. 43. Then bring either of the pairs of poles, N_1S_2 or N_2S_1 , near the pole of a compass needle; they will produce much less deflection than a single pole of one of the magnets would have produced, and a similar effect will be observed if we test them by their inductive action on a little bar as in fig. 37 or 38. It thus appears that the two magnets tend to neutralise one another *so far as the external field¹ is concerned*. Of course there is no diminution of polarity of *the magnets themselves*, it is simply that one pole more or less neutralises the *effect* of the other so that the pair possesses very little *free* polarity: in all cases it is *free polarity* that alone can produce an external field. A similar phenomenon is observed with the arrangement in fig. 44, or with any number of magnets of the same strength disposed so as to form a closed geometrical figure, the north pole of each touching the south pole of the next: such an arrangement possesses comparatively little free polarity.

Any such arrangement is called a *closed magnetic chain*.

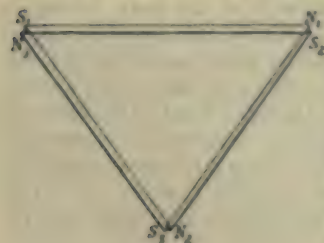


Fig. 44.

Suppose now that in a closed chain, *e.g.*, fig. 44, we separate two of the poles, say N_1 and S_2 , then the free polarity is at once increased and the external field strengthened: the chain is now said to be *open*. Of course with ordinary bar magnets we can never get *complete* neutralisation of external effect, partly because their thickness prevents their ends coming into contact at all points, and partly on account of

lateral polarity (§ 88). But if the magnets were simple magnets

¹ Any region in which magnetic action is exerted is called a magnetic field.

(§ 88), a closed chain made up of them would produce no external effect whatever. In other words, *a simple closed magnetic chain has no free polarity.*

91. Molecular Theory of Magnetism. This theory, which is the one now universally adopted and has been much elaborated by Professors Hughes and Ewing, supposes that *every molecule of a magnetic substance is a minute simple magnet.* How it comes about that such is the case is not known, but the property is supposed to belong to *the molecule itself*, and the molecules of an unmagnetised steel or iron bar possess it just as strongly as those of a magnet. What then is the difference between the two? Simply this, that *when unmagnetised, the molecules are so arranged as to form a number of closed magnetic chains while when magnetised the chains are more or less open.* The exact arrangement of the molecules in either case is unknown; in an unmagnetised bar it is probably of an altogether higgledy-piggledy character while in an ordinary bar magnet there is much evidence that the arrangement is as fig. 45. In this figure each little line N S



Fig. 45.

represents a molecule, and for convenience of drawing, gaps are left between the N of one molecule and the S of the next, though in reality they are supposed to touch. It will be seen that throughout the interior of the magnet every molecular pole touches an opposite pole of its neighbour so that the two neutralise one another and the interior possesses no free polarity; on the other hand, at the ends and along the sides all the molecular poles are free, which accounts for the terminal and lateral polarity of the magnet; the accumulation of free molecular north poles at the end A makes that end the N pole of the bar, while the free molecular south poles at B make that the S pole.¹

EXERCISE 1 :— How does the diagram indicate the gradual weakening of the lateral polarity from the poles to the equator?

¹ In the diagram only five chains of molecules are shown, but of course in reality there are many millions.

Fig. 46 shows an ideal arrangement of the molecules in a magnetised bar; it corresponds to the absence of lateral polarity, and

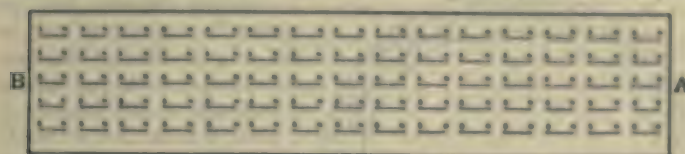


Fig. 46.

unless (§ 88) the bar be very thin does not fairly represent its true state; for convenience it is, however, usually adopted when, as frequently occurs, we are not concerned with the lateral polarity.

EXERCISE 2 :—Draw a diagram for a horseshoe magnet after the manner of fig. 46, and also after the more correct manner of fig. 45.

The molecular theory at once explains the effect of breaking a magnet (§ 89). For since the molecules are by their very nature unbreakable, the fracture must take place *between* and not *through* them; referring, then, to figs. 45 or 46, it is clear that each fractured face must contain an accumulation of free molecular poles, north on one and south on the other. The sudden freeing of these two sets of poles which, prior to the fracture, neutralised one another, accounts for the development of strong free polarity at parts of the magnet where previously none existed.

92. Internal and External Magnetisation. Circumferential Magnetisation. If we contrast fig. 45 or 46 with the higgledy-piggledy arrangement of the molecules in an unmagnetised bar, we see that although the interior of a magnet possesses no free polarity it is in a very different state from the unmagnetised bar; it possesses in fact what is known as *internal magnetisation*, the free polarity on the surface being termed *external magnetisation*. As we have seen (§§ 89, 91), as soon as the magnetised bar is broken or cut across, some of its internal magnetisation becomes external and manifests itself by acting on a compass needle, etc., but of course breaking an unmagnetised bar does not produce any such effect.

If we take a steel ring all cast in one piece it is possible by suitable treatment to magnetise it *circumferentially*, i.e., so that the molecules are arranged parallel to the circumference all round as in

fig. 47, without any of their poles abutting on the sides of the ring.



Fig. 47.

In this case the magnetisation is *entirely* internal and no matter how strong it may be the ring produces absolutely no external field, and affects a compass needle merely as a piece of neutral steel would do. But if we file through the ring at any part and then slightly separate the cut faces they at once exhibit free polarity, one northern and the other southern and produce the usual effects. If we reclose the ends these effects again in a great measure disappear, but never entirely as

the process of filing joggles some of the molecules out of place and develops more or less lateral polarity near the cut.

93. Other modes of Magnetisation. Irregular Magnetisation.

In addition to the modes of magnetisation indicated in figs. 45, 46, 47, there are innumerable others all of small importance. Thus it is possible to magnetise a bar so that its molecules set *sideways* more or less as in fig. 48. The poles of such a magnet would be its *faces* A B and C D, and when suspended so as to be free to turn horizontally, A B would face north-wards and C D southwards. Such magnets are rarely met with and, as will be explained in § 116, are difficult to make.

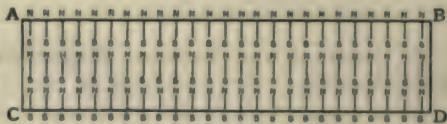


Fig. 48.

With regard to the bar and other magnets hitherto considered, they have been what may be termed *regularly* magnetised. The characteristic of such is that their poles are of equal strength and that their lateral polarity is uniformly distributed over the two halves, the magnetic equator being in the middle (cf. § 88). But it is quite possible to make *irregular* magnets for which these statements are not true. An irregular magnet may easily be made from a knitting needle by allowing one end to remain for several

minutes in contact with one of the poles of a strong bar or horseshoe magnet. Call the needle AB, and suppose we employ the N pole of the magnet and place it against the end A, then the needle will be magnetised so that the magnetic equator (E) is much nearer A than B, and the southern polarity will be concentrated from A to E while the northern will be diffused over the greater space from E to B. In any magnet whatever the *total* northern and southern polarity are equal, so that in the case considered the *end* A will have stronger polarity than the *end* B.

EXERCISES.—1. By what experiments would you prove all this?

2. Draw a diagram of the molecular arrangement in a circular steel plate magnetised radially, its centre possessing northern and its circumference southern polarity.

94. Explanation of Magnetisation. Magnetising Force. Magnetic Saturation. According to the molecular theory the process of magnetising a piece of iron or steel whether effected by simple induction or by any of the methods to be subsequently considered, consists in making its molecules rotate from a position in which all their chains are closed to one in which at any rate some of them are open, and as a somewhat curious piece of direct evidence in favour of this may be mentioned the facts that a bar is found to increase in length very slightly during magnetisation, and also that when suddenly magnetised by a strong electric current (§ 168) it gives a sharp click: both these circumstances appear due to some kind of molecular rearrangement. In § 103 we shall give a striking experiment in further support of this view.

Any influence tending to magnetise iron or steel is termed a *magnetising force*, and such a force exists in every magnetic field. Suppose now a neutral bar of iron or steel be subjected to a weak magnetising force, it ~~requires~~ acquires weak polarity; if then the magnetising force be increased it acquires stronger polarity, and so on. But the acquired polarity *does not increase indefinitely with the magnetising force*, there is a certain point which varies for different specimens, beyond which it is impossible to increase the polarity however great the magnetising force be made; this point is called *magnetic saturation*, and when the specimen has attained it it is said to be *saturated*. The explanation is that as the magnetisation increases *as more and more molecular chains are opened*, so soon as they are all opened of course the process must stop. *Magnetic saturation thus corresponds to the opening out of all the molecular chains.*

95. Explanation of Demagnetisation. When for any reason a magnetised bar sustains a diminution or loss of magnetisation we must, according to the same theory, regard it as due to a closing up of some or all of the molecular chains that were previously open.

All magnets tend to become weaker with time, so that this closing tendency would appear to be always present; its cause is doubtless the mutual attractions between unlike poles of neighbouring molecules though the exact manner in which these attractions operate is often difficult to trace.

96. Molecular Rigidity. We have already seen (§ 84) that it is more difficult to magnetise steel than iron, but that when magnetised it remains so far longer than iron. This is explained by supposing that magnetic substances offer a certain opposition to the rotation of their molecules which varies in different specimens, being very small indeed in soft iron but considerable in steel. The opposition in question is sometimes called *coercive force*, but this expression is open to objection: in place of it the term *molecular rigidity* is now more commonly employed; it is a mechanical property closely allied to that upon which hardness depends, for the harder a specimen

of iron or steel the more difficult it is either to magnetise or demagnetise—that is, the more opposition it offers to the rotation of its molecules.

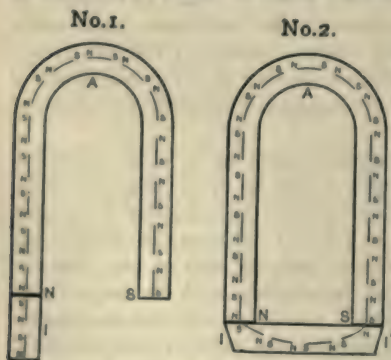


Fig. 49.

of molecular rigidity at all, but upon *making the magnet part of a closed magnetic chain*. This kind of retentivity and the explanation thereof will be clear from the following experiment:—A bent bar of soft iron, N A S (fig. 49), is surrounded by a coil of copper wire whose ends are

97. Retentivity. The power which a substance possesses of “retaining its magnetism” is called its *retentivity*; it is in general a consequence of molecular rigidity. There is, however, a kind of artificial retentivity or retention which does not depend upon mole-

connected to the terminals of a battery, so as to form an electro-magnet (§ 168).¹ The current being switched on, the bar becomes strongly magnetised, its molecules setting themselves all along it in the manner ideally represented by $N \rightarrow S \rightarrow S \rightarrow S \dots$. A piece of soft iron, I (No. 1), is placed against one of the poles, say N ; it adheres, being magnetised by induction, its molecules setting themselves as shown. The current is now switched off: instantly the piece I falls, the bar $N \rightarrow A \rightarrow S$ losing all its magnetism. Here there is no retention; while the current is on, the molecular chains are open, but as soon as it is switched off, owing to lack of molecular rigidity in the soft iron they close up in accordance with the tendency pointed out in § 95, resuming the higgledy-piggledy arrangement characteristic of neutrality.

We now again switch on the current so as to remagnetise the bar, and then place a piece of soft iron, II, across both poles (No. 2): it adheres, being magnetised by induction, and the molecules set as shown. The current is now switched off, and the piece II *does not fall*; it adheres almost as firmly as when the current was on, and may be made to support a considerable weight. Here we have the kind of retention in question, and the reason is *that the molecules of $N \rightarrow A \rightarrow S$ and of $I \rightarrow I$ taken together form a closed magnetic chain*.² Now, the molecules of a closed chain, unlike those of an open one, have but little tendency to rearrange themselves, hence on removing the original magnetising influence the condition of the bar remains practically unchanged. If now we detach the iron II by main force we destroy the closed chain, the higgledy-piggledy arrangement is at once resumed, and on again placing the iron across the ends N and S it will not adhere.

98. Keepers.—The piece $I \rightarrow I$ (No. 2, fig. 49) constitutes a *keeper* or *armature*; by its means the magnetism of the bar might be retained for many months. Keepers are commonly employed to assist in retaining the magnetism of permanent magnets, for even with steel of high molecular rigidity there is always a tendency for the molecules to go back towards their higgledy-piggledy positions if their chains be left open. The arrangement of a keeper attached to a permanent horseshoe magnet is the same as that of No. 2 above; it

¹ The diagram shows only what is essential to our present discussion the wire and battery are not depicted.

² Or rather a number of such; only one string of molecules is shown in the diagram.

is usual to put the magnet away in a box or on a hook with the keeper across it. With bar magnets the practice is to keep them in pairs, generally with a strip of wood between and a keeper at each end, as in fig. 50.



Fig. 50.

EXERCISES :—1. Draw a sketch showing the arrangement of the molecules in the bar magnets and keepers when placed in this way.

2. Would it do to employ keepers of hard steel? Give reasons for your answer.

In § 90 we have seen that a closed magnetic chain produces a very weak effect in the external field, hence we should expect that a pair of unlike magnetic poles with a keeper across them would exert but slight external action. That this is the case may be shown as follows :—Set a compass needle on a pivot so that it points N and S. Then hold some little distance from it a horseshoe magnet without a keeper so that it deflects the needle considerably. Then place the keeper across its poles ; the needle goes back nearly to its original position. (See also § 116.)

99. Consequent Poles. Magnets are sometimes made, either accidentally or intentionally, which instead of having simply a north pole at one end and a south at the other contain other poles. Thus there may be a north pole at each end and a south somewhere between ; or there may be a north at one end, a south at the other, and two intermediate ones, as in fig. 51, etc. All such intermediate

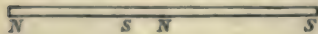


Fig. 51.

poles are termed *consequent poles*. There can never be two poles of the same kind without one of the opposite kind somewhere between. The explanation of consequent poles according to the molecular theory is made clear in fig. 52. Here A B represents a magnet with a north pole at each end and a south pole at some intermediate point, C;

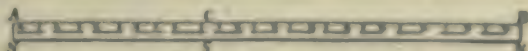


Fig. 52.

it will be seen that at C the south poles of two adjacent sets of molecules face each other; in other words, two molecular south poles follow one another instead of a north following a south as in the normal arrangement. This is the origin of the word "consequent" applied to such poles (the literal meaning is "following on"—Latin *consequor*). We have in fact, practically two magnets, A C and C B, with their south poles touching. Now, two poles of *opposite* kinds when placed together tend to neutralise each other so far as the external field is concerned, but the reverse is the case with two of the *same* kind, and hence it is that the point C exhibits strong southern polarity.

EXERCISES:—1. Two bar magnets are placed with the north pole of one against the south of the other: prove that although these poles weaken each other's effect on the external field they tend to preserve each other's actual polarity.

2. Two bar magnets are placed with the north pole of one against the north pole of the other: prove that though these poles strengthen each other's effect on the external field they tend to destroy each other's actual polarity.

3. How would you practically test a bar magnet for consequent poles?

100. Explanation of Magnetic Induction. Magnetic induction is readily explained by the molecular theory. Thus, in fig. 45 consider to begin with the bar A B in its neutral state with its molecules arranged higgledy-piggledy in closed chains, and suppose the south pole of a magnet then held near A. By the law of attraction and repulsion (§ 81) this south pole tends to turn all the molecular north poles towards A and all the molecular south poles towards B, thus making them take more or less the positions in fig. 45 or 46, so that A becomes a north and B a south pole in accordance with the law of induced polarity (§ 85).

In the case of soft iron the smallness of the molecular rigidity permits the molecules to turn round easily throughout the entire length of a fairly long bar, so that magnetisation by induction is easy. But in hard steel the molecules turn but slightly, and mainly near A, where the magnetic influence is strongest : this explains the experiment on irregular magnetisation in § 93. We thus cannot effectually magnetise a steel bar by simple induction ; to do so we must either move the inducing pole so as to bring it successively into the immediate neighbourhood of all the molecules (§ 101), or we must do something temporarily to diminish the molecular rigidity (§ 102), or, which is by far the best method, we must surround the whole bar by a strong electric current which places every molecule in a powerful magnetic field (§ 168).

101. Magnetisation of Steel by Rubbing. The simplest way of magnetising a steel bar is to rub it in a suitable manner with a magnet or magnets. There are three so-called "methods" of doing this ; they differ only in detail. The principle in each is the same—*viz.*, to bring each molecule of the steel in turn into the strongest part of the magnetic field in such a way as to make it turn in the desired direction. We shall consider the methods in order :—

Method of Single Touch. This is shown in fig. 53. A B is the bar to be magnetised. Suppose we wish the end A to become a north

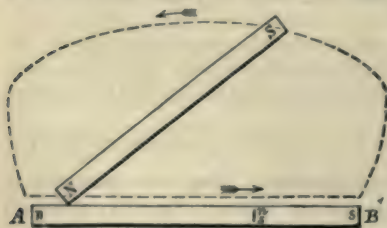


Fig. 53.

pole, we take a bar magnet, N S, and keeping it in a somewhat inclined position, draw its north pole from A to B, repeating the process a great many times, *but always stroking A B in the same direction.* Each time N arrives at B it is lifted and brought back at a distance from A B, so that on the

whole it describes the dotted line in the direction of the arrow.

The method may be modified by employing a horseshoe instead of a bar magnet, and stroking the bar from A to B with its north pole, and from B to A with its south pole. It will be observed that in all cases *the end of the bar where the stroking pole leaves it is of the kind opposite to that pole.*

The explanation of the action is as follows :—In fig. 53 consider a single molecule $a\ a'$ of the bar $A\ B$. This, to begin with, forms part of a higgledy-piggledy closed chain. As N approaches this molecule, it turns a somewhat towards B , but as it leaves it it turns a towards A . Thus every time N passes along, all the molecules of the bar are left with their north poles inclined towards A . The inclination produced at each stroke is small on account of molecular rigidity, but it accumulates, and after several strokes the bar is distinctly magnetised. It should, however, be noticed that the approach of N towards any molecule partly reverses the effect of its previous recession, so that after N has passed over it, it is left less inclined than it otherwise would be; thus the method is prone to produce weak magnetisation.

Method of Divided or Separate Touch. This is shown in fig. 54. Supposing we require the end A of the bar $A\ B$ to become a north pole, it is supported on the poles of two fixed magnets, A resting on a south pole



Fig. 54.

and B on a north. Two other magnets are then held in an inclined position with their poles as shown, and with these the bar is stroked a good many times from the middle outwards, bringing them back well above the bar, as indicated by the dotted lines: the final effect is to magnetise the bar as shown.

The explanation is similar to that of the method of single touch :—Every time the stroking pole N passes over a molecule $a\ a'$ it on leaving it inclines its north pole towards A , and the same is true of S as it passes over a molecule $a''\ a'''$. The stationary magnets help to keep the molecules in the inclined positions acquired, and thus to prevent the stroking pole reversing its previous action on approaching the molecule; the method thus produces stronger magnetisation than the preceding one.

Method of Double Touch. This is shown in fig. 55. The arrangement



Fig. 55.

is similar to that of the method of divided touch, except as respects

the movement of the stroking poles. The latter are kept a little distance apart by means of a pellet of wood or cork, and are moved *both together to and fro along A B*; thus starting at the middle, we move the pair of them to B, then back from B to A, then from A to B, and so on, finishing off at the middle.

Again the explanation is very similar: every time a molecule *n s* comes under the space between the stroking poles, it is in a magnetic field tending to incline its north pole towards A, but this field being much stronger than that at command in either of the previous methods, the resulting magnetisation is in general stronger. It will, however, be seen by reference to the diagram that the weak part of the field beyond the poles tends to turn the molecule the wrong way, not only as the pair of poles approaches, *but also as it leaves*; for this reason there is a possibility of the method producing consequent poles (§ 99), though as a matter of fact this rarely happens.

EXERCISE:—Describe how you would by the method of single touch (i) magnetise a knitting-needle so as to have a south pole at each end and a north in the middle; (ii) magnetise a ring circumferentially.

102. Effect of Heat and of Agitation. Every blacksmith knows that heat softens iron and steel. It diminishes their molecular rigidity, and we should therefore expect it would facilitate magnetisation and demagnetisation. This is actually the case. If we make a steel bar red-hot and hold it between the poles of a strong horseshoe magnet, allowing it to cool in that position, it is found afterwards to be well magnetised. Unfortunately, however, the gradual cooling softens it, so that it will not retain its magnetism well, and the method is therefore not a good one for the manufacture of magnets.

If a magnetised steel bar be made red-hot and then cooled away from magnetic influence it becomes demagnetised; here the molecular chains are open to start with, the heat diminishes the molecular rigidity, and they close up in accordance with their natural tendency (§ 95).

The effect of agitation is very similar. If we place one end of a knitting needle against a pole of a bar magnet and then hammer it so as to temporarily loosen its molecules while under the magnetising influence, it is afterwards found to be more effectually magnetised than if it had been left quiescent. In like manner hammering a magnet or allowing it to fall tends to demagnetise it.

103. Experiment in Illustration of the Molecular Theory. The view of the difference between magnetised and unmagnetised substances set forth in § 91, and the turning round of the molecules is strikingly illustrated by the following experiment:—Take a thin narrow glass tube, *a*, fig. 56, closed at both ends, and containing unmagnetised steel filings. Test it by a delicate magnetic needle as in § 82, to make sure that it is destitute of polarity. If the filings be looked at closely they will be seen to be arranged higgledy-piggledy. Now keep the tube firmly fixed, and stroke it from

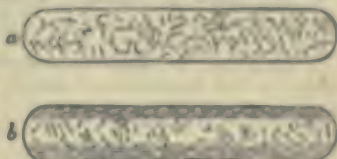


Fig. 56.

one end to the other several times with the north pole of a bar magnet, precisely as in the method of single touch: on watching carefully, many of the filings will be seen to place themselves lengthwise (*b*, fig. 56). Now test the tube by the magnetic needle: it will be found to possess distinct polarity, the end at which the stroking N pole left it being a south pole. Next shake the tube vigorously so as to make the filings resume their higgledy-piggledy arrangement and again test; all trace of polarity will be found to have disappeared.

The filings, therefore, behave both during magnetisation and demagnetisation very much as we have conceived the molecules of a bar to do.

EXERCISE—A glass cylinder with flat ends contains water in which is suspended finely divided magnetic oxide of iron. The tube has a coil of copper wire wound round it, and is fitted in a lantern so that the light falls on one of the flat ends. In front is placed a screen, and the circle of light on it is very dull. An electric current is now passed round the copper wire, when the light becomes much brighter. Explain this.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER II.

1. Effect of breaking a magnet (§ 89).
2. Magnetic chains. *A simple closed magnetic chain has no free polarity* (§ 90).
3. Cause of difference between unmagnetised and magnetised iron or steel, according to the molecular theory. Explanation of terminal and lateral polarity (§ 91).

4. The *interior* of a magnet possesses magnetisation but not free polarity. Circumferential magnetisation (§ 92).

5. Explanation of magnetisation and of magnetic saturation (§ 94); also of demagnetisation (§ 95).

6. The magnetic difference between iron and steel due to the greater molecular rigidity of the latter (§ 96).

7. Two kinds of magnetic retention, one due to molecular rigidity the other to the formation of closed chains (§ 97). Keepers promote the latter kind of retention (§ 98).

8. Consequent poles (§ 99).

9. Methods of magnetisation by rubbing (§ 101) especially the modified method of single touch in which both poles of a horseshoe magnet are used.

EXERCISES ON CHAPTER II.

1. You have a steel bar magnet and a steel knitting-needle, one end of which has been notched with a file. Describe exactly what you would do in order to magnetise the knitting-needle in such a way that when hung by a fine thread fastened to the middle, the notched end of the needle shall turn southwards.

2. You have three equal bar magnets without keepers. How would you arrange them so that, when not in use, they might preserve their magnetism? Give a sketch.

3. A glass tube with its ends marked A and B, and nearly full of steel filings, is stroked several times from A to B with the north-seeking end of a strong magnet. The tube is then brought with its end B near to the south-seeking pole of a compass needle. What is the effect upon the needle?

The tube is now shaken so as to mix the filings, and put near the needle as before. What is the effect upon the needle? Why is the effect on the needle different in the two cases?

4. A horseshoe magnet is placed near a compass-needle so as to pull the needle a little way round. On laying a piece of soft iron across the poles of the horseshoe magnet, the compass-needle moves back towards its natural position. Explain this.

5. It is suspected that a magnetised bar of steel has consequent poles. How would you ascertain whether this is so or not?

6. A bar magnet which has two consequent poles at its middle point is broken into two pieces. What will be the magnetic condition of each piece according as the break is made exactly at the middle point or at some distance from it?

7. A sewing needle is magnetised by stroking it from the eye to the point with the north pole of a steel magnet. How will the needle be magnetised? If it is then broken into three equal pieces, describe and explain the magnetic state of the fragments in relation to their positions in the unbroken needle.

8. Two rods of the same size, one of soft iron and the other of hard steel, are each rubbed from end to end with one pole of a strong bar magnet. How will the rods affect a compass-needle to which they are successively brought near.

* 9. Distinguish between terminal and lateral polarity, and show how the existence of both is explained by the molecular theory.

10. (1899.) A straight steel watch spring is magnetised and is then bent so that its ends are in contact. What effect would it have on a compass-needle to which it was brought near? And how would this effect be modified by the spring being cut into two parts while the original ends were still held together?

CHAPTER III.

MAGNETIC FIELD, FORCE, AND FLUX.

104. Different kinds of Field. The student will from the preceding chapter be already familiar with the term *magnetic field*; it simply means any region subject to magnetic influence. The simplest field is that due to a single "point-pole" such as belongs to a simple magnet (§ 88); strictly, however, it can exist only in imagination, for however thin a magnet may be it still falls short of the ideal simple magnet, and besides, we cannot obtain a magnet with one pole only. But we can obtain a very close approximation to such a field by using a long and fairly thin magnet and confining our attention to the region near either pole, which is practically uninfluenced by the other. The next simplest field is that due to two point-poles either of the same or opposite kinds. The field round an ordinary bar magnet is an approximation to the latter, while an approximation to the former may be obtained by placing two long bar magnets in a line, with like poles facing each other, the region between and near these poles being practically due to them alone. By placing two magnets in irregular positions, or by using several magnets, magnetic fields of varying degrees of complexity may be obtained.

The region outside a magnet or magnets is called the *external field*, that in the material of the magnets themselves the *internal field*. Whenever the field simply is spoken of, the *external* field is usually intended.

105. Force in a Magnetic Field. Consider any magnetic field, and imagine an isolated north pole¹ placed at an assigned point P

¹ That is "point-pole"; in future the context will in general indicate where the word "pole" is to receive this interpretation.

therein: it will experience a force in a certain direction and of a certain magnitude. The magnitude of the force depends, among other things, upon the strength of the pole; but its direction, with which alone we are at present concerned, depends only upon the nature of the field and the position of the point P.

Now we must be very careful what we mean when we speak of the "direction" of a force. A force may, for example, pull straight up or straight down; in both cases, in so far as it acts along *the same line*—*viz.*, a vertical one, its direction may be said to be the same, but the *way it pulls* is precisely opposite in the two cases. In mechanics the word "sense" is often employed to include both the line along which a force acts and the way it pulls, but in magnetism it is more usual to make the word *direction* include both these, thus we should speak of a force as having an upward direction or a downward direction.

Now if at our point P we place a *north* pole, it will be urged in a certain direction, but if at the same point we were to place a *south* pole it would be urged in a precisely opposite direction; when, however, any consideration is involved, not merely of the line along which the force acts, but of the way it pulls, it is invariably understood, in speaking of *the direction* of the force at a point, that we mean the direction in which a *north* pole placed at that point, would be urged. Sometimes for the sake of emphasis this is called the *positive* direction; the term, however, is hardly needed.

The force with which we are dealing is often called the *resultant* or *total* force at the point, in order to distinguish it from certain partial forces or "components," which will be introduced later.

Since in practice it is impossible to obtain an isolated pole, what we do is to employ a *very short, straight, and thin* freely suspended¹ magnetic needle; both its poles are then practically at the same point, and it sets itself along the line of the force at that point *with its north pole pointing in the (positive) direction of the force*. Such a needle, when used for examining the direction of the force at different points of a field, is spoken of as an *exploring* needle or *explorer*.

¹ A magnetic needle is said to be *freely suspended* when it is free to turn in all directions—*e.g.*, when supported at its centre of gravity by a piece of fine silk or cotton; a compass-needle (fig. 36) is not *freely* suspended, for its mode of mounting restricts its movements.

106. Exploration of a Field. The general method of using the explorer will be understood from fig. 57, where it is shown in various

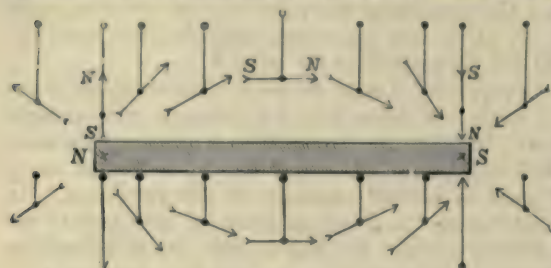


Fig. 57.

parts of the field of a bar magnet. Only one explorer is used; it is moved about from place to place, its direction then altering. The arrow-tip represents the north pole

of the explorer, and in all positions it is pointing in the direction of the resultant force. It will be observed that at the magnetic equator the line of the force is parallel to the bar, while near either pole it passes practically through one of the points marked \times . These two points are sometimes erroneously called the "poles" of the magnet (cf. § 119).

107. Lines of Force. A magnetic field may be explored in an easier and more striking way by means of fine iron filings. We place a sheet of glass or stiff white cardboard over the magnet (or magnets), and then loosely and evenly scatter filings over it from a pepper-box or flour-dredge provided with fine holes. Each filing becomes by induction a little magnet, and is ready to act as an explorer provided it were free to turn. This, however, it cannot do on account of the friction of the sheet; we therefore gently tap the latter so as to jolt the filings a very little way up; each one then sets itself in the line of the resultant magnetic force at the particular point it occupies, and falls in the position thus acquired. The filings therefore arrange themselves in definite curves: these curves are called *lines of force*. Now considering any point, P, on one of the curves it is obvious that the filing at P lies along the tangent¹ to the that curve at P; whence, since the filing also lies along the direction

¹ By the tangent to a curve at a point is meant a straight line which *just grazes it* at that point; a more elaborate definition is given in mathematical books, but this is all it really amounts to.

of the magnetic force at P, it follows that *the tangent to any one of the curves at any point on it is in the direction of the magnetic force at that point*; this is a most important property and the one whence the curves derive their name. It should be noticed, too, that in the strict sense of the term the "lines of force" are mere geometrical lines in the field possessing the property in question, and exist *in the absence of the iron filings*; the latter serve merely to render them visible to the eye. The term *magnetic curves* is sometimes used to distinguish the lines thus rendered visible from the mere mathematical lines.

Lines of force have numerous uses in the higher part of the science of magnetism, and also in electrical engineering; their immediate and most valuable elementary characteristic is that by virtue of the foregoing property they afford us a bird's-eye view of the direction of the magnetic force at any and all points of the field.

It should be noticed that the lines of force in any field always *run clear of one another*, i.e., no two can intersect, for if they did it would indicate that the force at the point of intersection was in two different directions, which of course is absurd.

In § 105 we have explained what is meant by the (positive) direction of the force at a point in a field. In like manner by the (positive) direction of a *line of force* is meant the direction in which an isolated north pole would travel along it if free to move, or that in which the north pole of an explorer or a filing points.

In examining a field by an explorer we can always tell the positive direction because the north pole of the explorer is marked, but this is not the case with the filings; usually, however, we know beforehand which is the general positive direction (e.g., in the field of a bar magnet we know that it runs *from* the north *to* the south pole), and merely want the filings to show the specific forms which the lines take.

It is usual in diagrams to employ arrows to indicate the positive direction of the lines of force (cf. § 109).

108. Special Cases of Lines of Force. The form of the lines of force varies according to the nature of the field. The simplest field is that due to a single pole (§ 104): they are then straight lines passing through the pole. If the pole be a north one their positive direction is *from* it, if a south one *towards* it. They may be approxi-

mately shown by setting a long bar magnet vertically, placing a piece of cardboard over its upper end and sprinkling filings on it: on gently tapping the cardboard the filings will arrange themselves in straight lines passing through the pole.

A very important field is that due to an ordinary bar magnet, and fig. 58 shows the lines of force in this case.¹ They form a series of oval curves many of which strike not the ends but the sides of the magnet; this is on account of lateral polarity (§ 88). With a very thin magnet most of them strike the ends, and in the ideal simple magnet they would *all* do so (see fig. 71, p. 131).

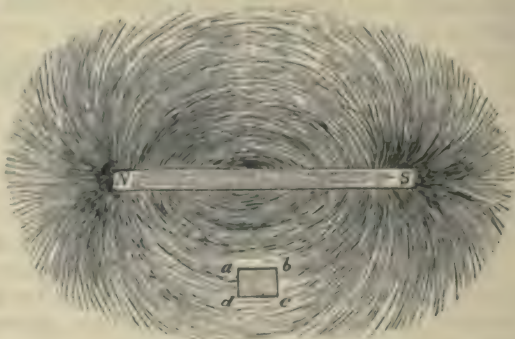


Fig. 58.

The central portion of fig. 59 exhibits the lines of force in a field due to two unlike poles of equal strength *separated by an air space*;

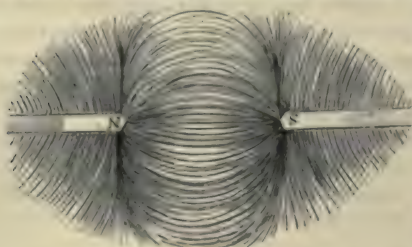


Fig. 59.

the poles are those of two long bar magnets placed as shown, and it will be observed that the lines in this central portion *do* all strike the ends of the magnets, the air space of course possessing no lateral polarity. To the right and left we have parts of the field where the influence

of the other poles of the magnets is distinctly felt; here the lines resemble those in fig. 58.

¹ The piece of iron *a b c d* shown in the figure is for another purpose: see § 110.

Fig. 60 depicts the field of a horseshoe magnet. The region above the line joining the poles is precisely similar to that in fig. 59, while between the prongs the lines of force are nearly straight: here and also on the outer sides of the prongs we have the effect of their lateral polarity.

Fig. 61 shows the field of a pair of like poles of equal strength; it will be seen that the lines of force from each pole bend away from the other, and the two sets meet in cusps. The curves to the right and left of the poles belong to other parts of the field, where the influence of the south poles is distinctly felt.

It will be noticed in all these figures that no filings collect *actually over the magnets*, or at any rate they do not there arrange themselves in definite curves. This is sometimes said to be because there are in this part of the field no lines of force, but that is of course absurd, the whole region round the magnets is a magnetic field, and lines of force strike them on the top just as much as on the sides. But as these lines are in vertical planes the magnetic action would tend to make the filings

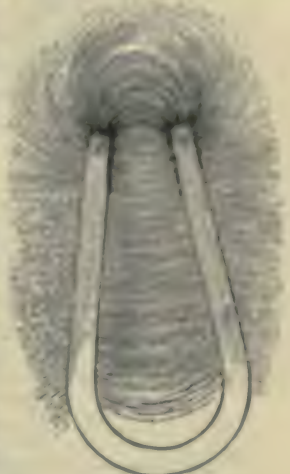


Fig. 60.

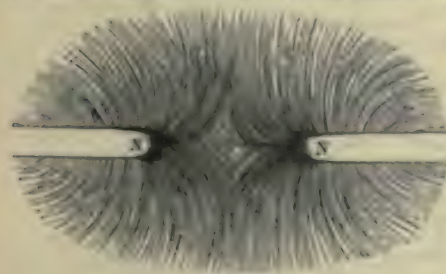


Fig. 61.

stand more or less on end, and this their weight prevents them from doing, consequently they fall into positions unfavourable to the inductive action of the field, and simply get joggled off. If, however, the magnets be very strong it is quite possible to get a good many of them to stand on end in the way described.

109. How to sketch Lines of Force. Students are frequently required to make neat sketches of the lines of force in simple magnetic



Fig. 62.—Single North Pole.

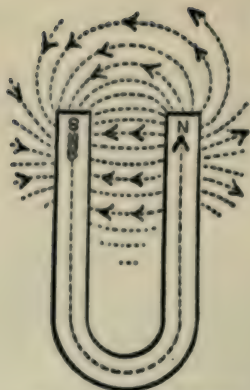


Fig. 63.—Horseshoe Magnet.

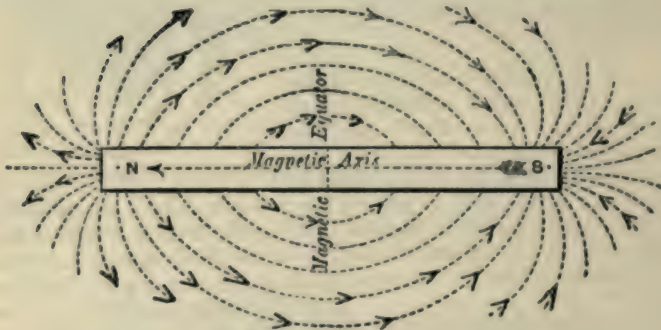


Fig. 64.—Bar Magnet.

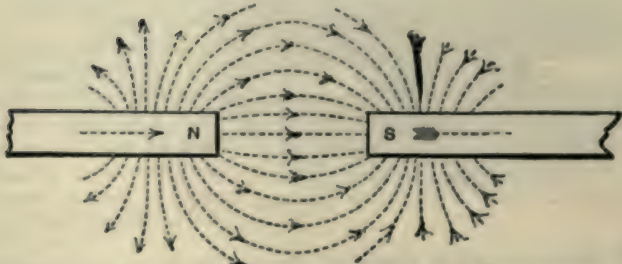


Fig. 65.—Air-space between two Unlike Poles.

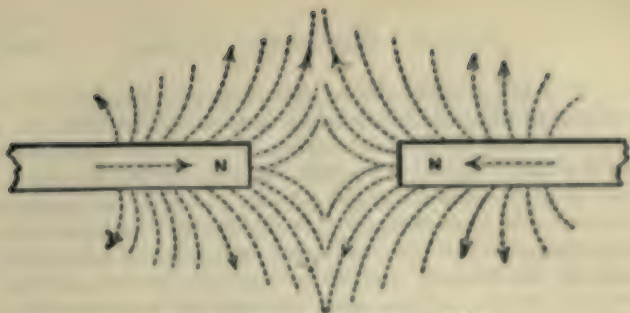


Fig. 65.—Air-space between two Like Poles.

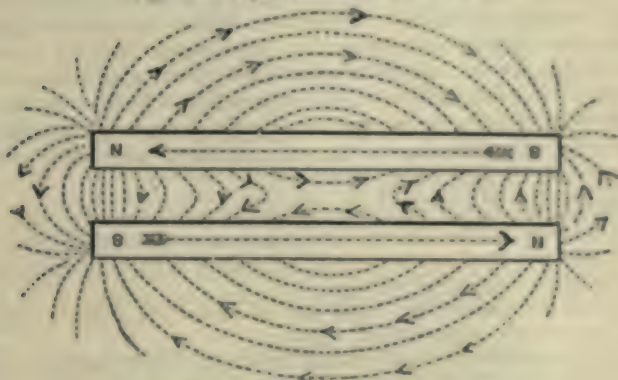


Fig. 66.—Pair of Parallel Opposed Bar Magnets.

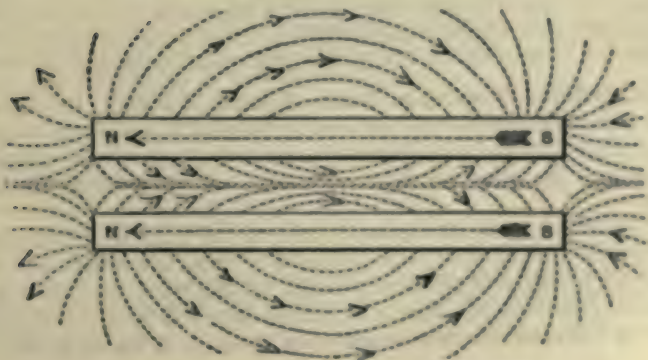


Fig. 68.—Pair of Parallel Concurrent Bar Magnets.

fields. It is best to make them diagrammatic rather than pictorial, and we append diagrams for the most important fields (figs. 62—68). It is very essential in all cases to notice (§ 107) which is *the (positive) direction* of the lines, and when this has been settled it is usual to indicate it by arrows marked along them. Thus in fig. 64 which is the diagrammatic form of fig. 58, it is obvious that an isolated north pole placed anywhere in the field would tend to travel away from the N pole of the magnet, and accordingly we put in arrows, as shown; the arrow is always made to point the way the north pole would travel. All the rest of the diagrams explain themselves and should be carefully studied. The curves *between* the magnets in figs. 67 and 68 are somewhat peculiar, but comparison with the standard cases of figs. 64, 65, and 66 should enable us to recall them when necessary; thus in fig. 68 the lines between N and S resemble those in fig. 66, while those between the central parts of the magnets resemble those in fig. 64. Reference to the same standard cases often enables us to predict the lines for other fields.

EXERCISES (N.B. The sketches will be found among the answers at the end of the book, but the student should try them well before looking):—

1. Sketch the lines of force for a bar magnet with consequent poles one-third of its length from each end.

2. Sketch the lines of force for a pair of similar bar magnets crossing each other at right angles at their centre.

* 3. Six bar magnets of equal strength are arranged with their poles round the circumference of a circle at equal distances apart; a north and a south pole following one another alternately, and all the magnets pointing towards the centre of the circle. Draw a diagram of the lines of force within the circle. (NOTE.—This diagram is of importance to the electrical engineer in connection with the theory of multipolar dynamos.)

110. Induced Polarity in Terms of Lines of Force. In § 85 we have given a simple law for the polarity induced in a piece of iron or steel when subjected to a magnetising influence, and we now proceed to consider the same law in a more extended and often preferable form.

In fig. 38(a), p. 96, the lines of force on the right of the magnet N S run (following their positive direction) from right to left, and the little bar *ns* acquires southern polarity on the right, *i.e.*, where the lines of force enter it. Now it is just the same whatever field we are dealing with, and wherever we place the iron; *e.g.*, in fig. 58, p. 124, if

$a b c d$ represent a piece of iron placed in the position shown, its side $a d$ will acquire southern and $b c$ northern polarity. We have then the following perfectly general law—viz., that when a piece of previously neutral iron, steel, or other magnetic substance is placed in a magnetic field it acquires southern polarity where the lines of force enter it and northern where they leave it.

EXERCISE:—Two bar magnets are placed in a straight line with their north poles facing one another, and a soft iron rod is placed between and in a line with them. How will it be magnetised?

*111. **Intensity of Magnetic Field.** Consider any point, P of a magnetic field, and imagine an isolated point-pole placed thereat. Then the magnitude of the force on it will depend among other things upon its strength. Now there is a certain standard strength of pole called the *unit pole*,¹ and if we suppose the pole placed at P to have this standard strength, the force on it will depend only on the character of the field and the position of P , and this force is called *the intensity of the field at the point P* . It is usual to estimate the intensity in *dynes*, a dyne being practically 36 millionths of an ounce, thus when we say the intensity of a field at a certain point is 20, we mean that a unit pole placed at that point would experience a force of 20 dynes.

Since any force has both magnitude and direction, it is clear that intensity of field has both magnitude and direction, i.e., is a "vector" or "directed" quantity.

*112. **Tubes of Force. Magnetic Flux.** In mapping out lines of force by iron filings or drawing them on paper we are obliged to confine ourselves to the part of the field in the plane of the paper, but of course the lines exist in the entire field. Consider then any field, e.g. a room in which there are magnets. It is full of lines of force, and we may fix our attention upon as many or as few of them as we please. Let us in imagination pick them out in such a way as to enclose a number of little tubes; these are called *tubes of force* and resemble pipes whose breadth is in general different at different parts: see $A B C D$ fig. 69. The tubes may be conceived as drawn to any scale we please, but it is usual to adopt a certain scale based upon considerations belonging to the higher parts of the subject, and when drawn to this scale they are called *unit tubes*.

Now these unit tubes possess the property that they are narrow in the strong parts of the field and broaden out in the weak parts, the strength



Fig. 69.

¹ This is exactly defined in the mathematical parts of the subject.

of the field being in fact inversely proportional to the cross section of the tube; thus, in fig. 69 if the area of the section $P'Q'$ be four times that of the section PQ , the field will be four times as strong at PQ , as at $P'Q'$. Let us now imagine the whole field mapped out in unit tubes, so that the particular one shown in fig. 69 is surrounded by others, and let us imagine a certain area, say a square centimetre,¹ placed so as to overlap PQ , and another equal area placed so as to overlap $P'Q'$. Then clearly if $P'Q'$ have four times the area of PQ , four times as many tubes will fall on the square centimetre at PQ , as on the one at $P'Q'$. It thus appears that the strength of the field at any point is directly proportional to the number of unit tubes that fall in a square centimetre, placed at that point perpendicular to the sides of the tube. Adopting the definition of intensity or strength given in the preceding article, it is shown in the mathematical parts of the subject to be not merely proportional but *equal* to that number, *e.g.*, if there were $17\frac{1}{2}$ tubes per square centimetre at a particular part of the field, the intensity there would be $17\frac{1}{2}$.

Now the number of unit tubes that fall in any area placed perpendicular to their sides is called the **MAGNETIC FLUX**, or simply the **FLUX** across that area; we thus have the theorem that *the intensity of a magnetic field at any point is equal to the flux per square centimetre at that point.*

This theorem, and the conception of magnetic flux generally, are of very great importance, and are specially commended to students of Electrical Engineering, as they are the basis of the whole theory of the action and design of dynamos, transformers, etc

The student should cultivate the habit of picturing to himself any magnetic field as riddled with unit tubes whose characteristic feature as above explained is that they *narrow up in the strong parts of the field and broaden out in the weak ones*, thus affording a heavy flux in the former and a light one in the latter.

Electrical engineers frequently speak of the number of "lines" of force that fall on a given area. Strictly, this phrase can have no meaning, for *every point* of a magnetic field has a line of force passing through it, and the number of lines that strike any area must therefore be infinite; whenever the term "lines" is used in this connexion it must be understood as meaning *unit tubes*, the "number of lines" per given area signifying the *flux* across that area.

If we now turn to figs. 58—71 it will be seen that the filings congregate most closely near the poles of the magnets, *i.e.*, in the strongest parts of the respective fields; this is what always happens—the filings, for reasons

¹ See foot-note, page 74.

into which we need not enter, do not map out the whole infinitude of lines of force but select certain ones, and indicate roughly the unit tubes, so that an inspection of them gives a general idea of the relative intensity of the several parts of the field. *Diagrams* also (cf. figs. 62-68) when well drawn do the same thing.

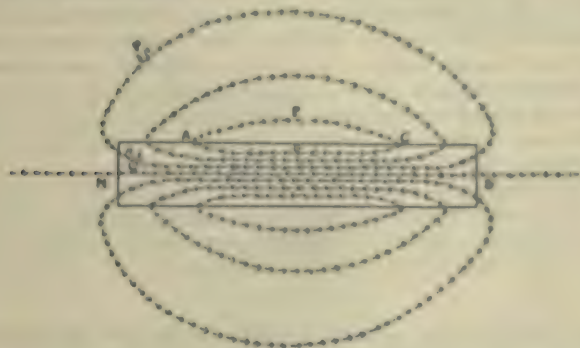


Fig. 70.

***113. Internal Field. Lines of Induction. Magnetic Circuit. Leakage.** The *actual substance* of a magnet whether a permanent one or otherwise (§ 84) is a field of magnetic force just as truly as the region outside, and constitutes the *internal field*; the positive direction of the

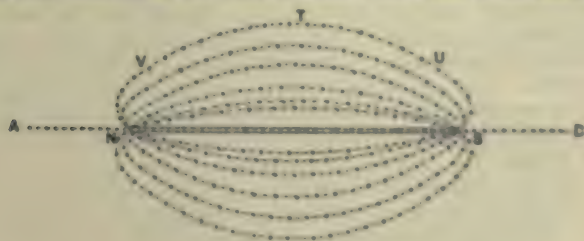


Fig. 71.

line of force at any point of this field is (cf. § 107) that in which an isolated north pole placed at that point would travel, provided its motion were not impeded by the substance of the magnet.

Internal lines of force are frequently termed *lines of induction*.

Figs 70 and 71 show the arrangement of the lines of induction and of

force for an ordinary bar magnet and a simple magnet respectively, the arrows indicating their positive direction,¹ and the diagrams bring out two very important points which are true not only for the magnets here considered but in every possible case: these are:—

1. That when any line of induction, *e.g.*, C Q A, fig. 70, emerges from the magnet it is *continued without any break* into a line of force, A P C, in the external air, and similarly when any line of force enters the magnet it is continued into a line of induction. Any complete line of force, *i.e.*, internal and external together, thus constitute a *closed curve*. One or any collection of such closed curves is called a *magnetic circuit*. The trespassing of lines of force into any place when they are not wanted is spoken of by electrical engineers as *leakage*; we may accordingly say that the internal lines “leak” out at the sides of the bar magnet.

2. That free polarity is always exhibited on those parts of the surface of the magnet *where the internal lines emerge into the air, and nowhere else*; thus in fig. 70 their leakage at the sides is accompanied by lateral polarity, while in fig. 71, which represents the simple magnet, all the lines emerge at the ends.

***114. Internal Flux. Case of a previously Neutral Bar placed in a Magnetic Field.** The lines of force in the actual substance of a magnet will aggregate themselves into unit tubes, which, when they emerge into the external field, run direct into the unit tubes of force of the air-field, completing the magnetic circuit. We thus have not only an external but also an internal flux.

By far the most important case is that of a previously neutral bar of iron (steel or other magnetic substance) introduced into a magnetic field. It then becomes magnetised by induction in accordance with the law of § 110 and acquires of course, not only surface polarity, but also (§ 92) internal magnetisation. Now it is shown in the higher parts of the subject that in general, *by virtue of the internal magnetisation*, the flux within the iron becomes vastly greater than it was in the same part of the field when the iron was absent. The numerical relations between the two varies, however, a good deal according to circumstances, and depends among other things upon the length of the bar and its direction relative to the lines of force of the field; according to the researches of Professor Ewing a flux of 5 (unit tubes per square centimetre) in air produces a flux of about 10,000

¹ It is a point for discussion whether the molecules of a magnet (*cf.* fig. 45) set themselves exactly along its lines of induction, though their general trend is certainly the same: the matter will not, however, concern us.

in long bars of good wrought iron set lengthways in the field, but if the bars be short or if set sideways the flux produced is decidedly less.

***115. Magnetic Susceptibility and Permeability.** DEFINITION 1.—*The power which a previously neutral substance possesses of acquiring polarity or internal magnetisation when subjected to magnetic influence is called its SUSCEPTIBILITY.* As a definition this applies to all substances magnetic or otherwise, but it is only in the magnetic ones that the susceptibility is appreciable.

DEFINITION 2:—*The power which a previously neutral substance possesses of acquiring a flux when subjected to magnetic influence is called its PERMEABILITY.*

In the preceding article it has been mentioned that the high flux acquired by magnetic substances is due to their internal magnetisation; it thus appears that susceptibility and permeability are two closely associated properties, and that the greater the one the greater the other. In the higher parts of the subject both are defined in mathematical terms, and a definite relation established between them.

The permeability of all magnetic substances as compared with that of air is enormous, and follows the order of their susceptibility; thus it is greatest for annealed wrought iron and cast dynamo-steel (§ 84) while for other materials it is considerably less. The permeability of all non-magnetic substances such as copper, brass, wood, etc., is practically equal to that of air.

***116. Practical View of Permeability; Principle of Least Reluctance.**

In the early days of the science of magnetism attention was devoted exclusively to poles and surface polarity, but at the present time far greater importance is attached to fluxes and permeability, chiefly because they are much better adapted to the needs of the engineer.

For practical purposes the best view to take of permeability is this:—We regard every substance as offering a certain amount of opposition to the passage of lines of force, this opposition being termed magnetic *reluctance*, or (to put the same idea another way) as possessing a certain power of transmitting or conducting the lines. Permeability then simply means conducting power or the reverse of reluctance. Suppose now we have a field occupied partly by air and partly by iron; the lines of force will, so to speak, try to get through it *with as little trouble as possible*, or as it is technically expressed *will pursue the path of least reluctance*; they will therefore tend to crowd themselves into the iron, thus making the unit tubes narrow and the flux dense, while in the air they will tend to spread

themselves out, making the unit tubes broad and the flux light. This principle is known as the *Principle of Least Reluctance*.

Consider now fig. 72, which when contrasted with fig. 60, p. 125, shows the effect of placing a keeper across the poles of a horseshoe magnet. In both cases the lines of force which emerge from the north pole have to get round to the south pole. In fig. 60 the only path open to them is the air and as this possesses small permeability they are obliged to spread themselves out into it so that there is a bountiful flux and a fairly strong field for some distance beyond the poles. But in fig. 72 the keeper affords a very much easier path, accordingly the lines travel almost entirely through it, and except for leakage none enter the air field beyond, so that the latter is very much weakened.



Fig. 72.

One consequence of the principle of least reluctance is that, if there is, so to speak, much to be gained by the lines of force taking a certain path, they will do so, but if there is little to be gained they will not trouble much about it. This explains why it is easier to magnetise a bar *lengthways* as in fig. 45, p. 106, than *sideways* as in fig. 48. For, suppose the bar, say, a foot long and half an inch square; if set lengthways in the field the lines of force by going through it can save themselves a foot of air-path, which is well worth doing, and accordingly they crowd into it producing a dense internal flux and strong magnetisation. But if it be set sideways, the lines by going through it can only save half an inch of air path which is not worth doing; accordingly the flux through it is scarcely denser than it would be through air, and the magnetisation is feeble.

EXERCISES:—1. A keeper is placed across the poles of a horseshoe magnet but with about half an inch air-space between; draw a diagram showing the path of the lines of force from pole to pole, and explain it in accordance with the principle of least reluctance.

2. (1903.) A bar magnet lying on a table about a foot from a compass needle produces a certain deflection of the needle. How is the deflection altered (if at all) when an iron bar the same size and shape as the magnet is placed on the top of the magnet?

3. A single pole of a horseshoe magnet can support only a small weight, perhaps an ounce. But if a piece of iron be placed across both poles the magnet can support a far greater weight, perhaps four to five pounds. Explain this.

***117. Magnetic Screens.** The great permeability of magnetic substances enables them under certain circumstances to act as magnetic screens. Thus fig. 73 shows in horizontal section a thick cylindrical pot of cast dynamo-steel placed between opposite poles of two strong magnets, and it is found that if a compass needle be placed inside the pot it is very little affected, the reason being that the lines of force that would otherwise occupy the air-space within the pot are crowded into the actual material of its sides, as shown.

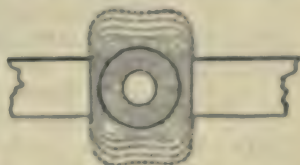


Fig. 73.

Fig. 74 shows the screening action of a broad thick iron plate, the lines of force from the magnet bending themselves round and travelling through it as shown, in order, as explained in the preceding article, to "save themselves the trouble" of going through the air; the part of the field behind the plate thus receives a very feeble flux, and the needle is scarcely affected. It is clear that the screening will be more efficient the broader the plate, because this will afford a longer path in the iron and so save the

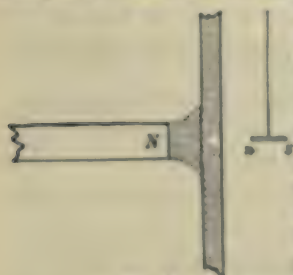


Fig. 74.

lines more trouble. It is also more effective the *thicker* the plate, because this allows the lines to crowd into it without burdening it with too heavy a flux; the effect of the latter would be to cause leakage—indeed, however thick the plate (or pot in fig. 73) may be, there is pretty sure to be *some* leakage, so that it is very difficult to obtain *perfect* magnetic screens; in this respect they present a striking contrast to *electric* screens (§ 53), which can be rendered perfect when made of thin metal or even metal gauze.

The student should guard against the not uncommon error of supposing that a magnetic screen can act by *breaking off* the lines of force; this cannot possibly happen, they are never broken but only deflected into another part of the field.

EXERCISE:—Two bar magnets are placed in a line with unlike poles facing one another, a sheet of cardboard is placed over them, iron filings sprinkled upon it, and the cardboard tapped. A piece of thick, soft iron pipe is then placed vertically beneath the cardboard and the latter again tapped. What difference (if any) will be made in the arrangement of the filings?

118. Uniform Field. Directivity of Uniform Field. If the intensity at every point of a magnetic field is the same, *both in magnitude and direction* (§ 111), the field is said to be *uniform*; in such a field the lines of force are all straight and parallel as in fig. 75.



Fig. 75.

Now consider a uniform field and let the dotted line *a* (fig. 76) be the direction of its lines of force. Let a straight simple magnet (§ 88) *ns* be placed in the field in a direction *not* coincident with its lines of force. Then the needle experiences equal forces, *P* and *Q*, on its two poles, each parallel to *a* but in opposite directions, and, as fully explained in mechanics, the effect of these is to *turn the needle round* until it sets parallel to *a*, but in no way to make it *move bodily*. If however the field be *non-uniform*, the forces in the poles are not equal and parallel, and they make the needle not only take up a definite direction but also move as a whole.

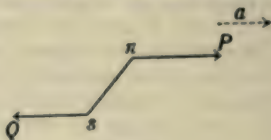


Fig. 76.

In the higher parts of the subject it is shown that the same effects are produced on *any magnet whatever*.

These results are usually expressed by saying that a *uniform field is purely directive*, while a *non-uniform field is both directive and translatory*: they will be of service in the next chapter.

EXERCISE:—Show that in a uniform field the unit tubes are all of the same sectional area.

119. Precise Meaning of Poles. Magnetic Axis. If in the preceding article we employ any magnet other than a simple one, the forces of the field are distributed irregularly all over its surface. But it may be shown on mechanical principles that *if the field be uniform* their action on the magnet is precisely the same as if all its northern polarity were concentrated at a certain point within it, and all its southern polarity at a certain other point within it. These two points are defined as the *true poles* of the magnet, and are what must always be understood whenever the word “poles” is applied in the sense of definite points to magnets in general. And it should be expressly noticed that it is *only* in respect of the action between the magnet and a uniform field that the poles can be regarded as repre-

senting the actual magnet : a magnet, in fact, unless it be a simple one, has in a general sense no point poles whatever.

The line joining the poles of a magnet as above defined is called the *magnetic axis* ; in the case of a properly magnetised thin needle, or a compass needle of the shape shown in fig. 36, p. 94, it practically coincides with the line joining its tips.

In a properly magnetised bar magnet the poles are somewhere about the position of the points marked * * in fig. 57, p. 122, but a little further from the ends.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER III.

1. Meaning of a Magnetic Field (§ 104).

2. *The (positive) direction of the force at any point of a field is the direction in which an isolated north pole placed at that point would be urged, or in which the north pole of an explorer situated there would point* (§ 105).

3. *Lines of force* are geometrical lines in a magnetic field, which possess the property that the tangent to any one of them at any point thereon is along the line of the resultant force at that point. *The (positive) direction of a line of force is the direction in which an isolated north pole would travel along it if free to move.* The lines of force of a field always run clear of one another. The visible forms which the lines take when mapped out by iron filings are called "magnetic curves" (§ 107).

3. Special cases of lines of force, particularly figs. 58, 59, 60, 61, and the corresponding diagrammatic forms, figs. 64, 65, 63, 66. In all cases note the positive direction as shown by the arrows.

4. When a piece of previously neutral iron or other magnetic substance is placed in a magnetic field, it acquires *southern* polarity when the lines of force *enter* it and *northern* when they leave it (§ 110).

*5. Meaning of Intensity of Field (§ 111).

*6. Every magnetic field is to be pictured as riddled by *unit tubes of force* ; these are narrow in the strong parts of the field and broad in the weak parts. The number of them that strike any area perpendicular to their sides is called the **MAGNETIC FLUX** across that area, and *the flux per square centimetre at any point of the field is equal to the intensity at that point.* When the Engineer speaks of the number of "lines" of force he means unit tubes (§ 112).

*7. Lines of force in the actual substance of a magnet are often called *lines of induction*. The lines of induction and of force together constitute a set of closed curves forming the *magnetic circuit*. Free polarity is only exhibited when the lines of induction strike the surface of the magnet (§ 113).

*8. When a previously neutral bar of iron or other magnetic material is placed in a magnetic field it acquires a much greater flux than existed in the same part of the field before it was put there, and it does so by virtue of its internal magnetisation (§ 114).

*9. Definitions of SUSCEPTIBILITY and PERMEABILITY (§ 115). The permeability of all magnetic substances as compared with that of air is extremely great and follows the order of their susceptibility.

10. *Principle of least Reluctance* and its use to explain various magnetic phenomena (§ 116).

*11. Magnetic screens depend for their action upon their high permeability. They do not *break off* the lines of force but draw them into their own substance and so away from the part of the field it is desired to screen. They must be thick, and even then are never perfect on account of "leakage" (§ 117).

12. By a *uniform field* is meant one at every point of which the intensity is the same, both in magnitude and direction: in such a field the lines of force are all straight and parallel to one another. A *uniform field is purely directive*; but a *non-uniform field* is both *directive and translatory* (§ 118).

13. When *any* magnet is placed in a uniform field we may regard the whole magnet as represented by the specific points at which its polarities are concentrated, but except in the case of a simple magnet we cannot do so under any other circumstances; these points are the "poles" of the magnet in the precise sense. The line joining these poles is called the *magnetic axis* (§ 119).

EXERCISES ON CHAPTER III.

1. An iron ball is held over a pole of a horseshoe magnet. Will the attraction exerted on the ball be altered if the poles of the magnet are connected by a soft iron keeper, and if so, in what way, and why?

2. Three precisely similar magnets are placed vertically, with their lower ends on a horizontal table. Iron filings are scattered over a plate of glass which rests on their upper ends, two of which are north poles and the third a south pole. Give a diagram showing the forms of the lines of force mapped out by the filings.

3. A long magnet and a piece of soft iron of the same size and shape are placed parallel to each other underneath a sheet of paper upon which iron filings are strewed. How will the filings arrange themselves?

4. Iron filings are scattered on a piece of cardboard, which is placed over a horseshoe magnet and tapped. What difference would be observed in the arrangement of the filings when the ends of the magnet were joined in turn by bars of (1) soft iron, (2) steel, and (3) copper?

5. Explain why in the process of magnetising a steel bar by either of the methods of single, divided, or separate touch, we hold the rubbing magnets in an *inclined* position.

6. (1903.) A compass needle is placed one foot east from a short bar magnet which points towards it. How will the needle be affected (i) when a thick box of soft iron is placed over the needle, (ii) when the box is placed over the magnet.

7. (1900.) Two equal magnets of the same strength are placed on a horizontal table parallel to each other and perpendicular to the line joining their centres, with similar poles in opposite directions. What changes would take place in the magnetic field produced by them close to the surface of the table if they were gradually moved parallel to themselves until they were in contact along the whole of their lengths? Give diagrams showing how your statement might be tested by means of iron filings.

* 8. Write a short essay on tubes of force and magnetic flux, pointing out the connexion between the flux at any point of a field, and the intensity at that point.

* 9. Define the terms magnetic permeability and susceptibility, and point out in a general way without mathematics how the two are related.

* 10. What do you understand by magnetic reluctance, and by the "principle of least reluctance"? Explain in accordance with this principle, why a long iron bar becomes more effectively magnetised than a short one when subjected to the same magnetising influence.

11. What do you understand by a uniform magnetic field? By what special property as respects its action on a magnetic needle is such a field distinguished from any other?

12. What are the "true poles" of a magnet, and under what circumstances do they represent the actual magnet? Define the magnetic axis.

CHAPTER IV.

TERRESTRIAL MAGNETISM.

120. The Earth regarded as a Magnet. We saw at the commencement of the subject that a compass-needle sets itself (approximately) north and south, and we agreed to call the pole which points northwards the *north pole*. There must clearly be some influence in the northern regions of the earth tending to attract that pole, and likewise an influence in the southern regions tending to attract the south pole. The earth, in fact, behaves like a huge magnet whose south pole is in its northern regions and whose north pole is in its southern, and it is accordingly agreed to look upon the earth as such a magnet: we do not however in any way commit ourselves to the *cause* of its magnetism.

The fact that the northern regions of the earth behave like the south pole of a magnet—that is, attract the north pole of another magnet—is the source of the confusion of nomenclature referred to in § 80: those writers who speak of the pole of a magnet which points to the north as the “south pole” intend thereby to call attention to the fact that it possesses the same kind of polarity as exists in the southern regions of the earth. But nothing is really gained by this phraseology, and we shall adhere to that hitherto employed. The pole which points *northwards* we term the *north pole*, and the kind of polarity which exists in the north pole of a magnet we term *northern polarity*. *The northern regions of the earth therefore possess southern polarity, and its southern regions northern polarity.*

121. The Earth's Magnetic Field. Line of Dip. Intensity of Earth's Field. The whole region on and around the earth's surface is a magnetic field and may be explored like any other magnetic field by the method of § 106. It is of course permeated by lines of force, and the explorer always points along them with its north pole in their positive direction. The line along which the explorer sets at

any point is called the *line of dip*, and is the direction of the earth's resultant force at that point. The intensity of the earth's field at a point is in accordance with the general definition of intensity (§ 111), the force which unit pole there situate would experience; sometimes this is called the *total* or resultant intensity to distinguish it from the horizontal and vertical intensities (§ 122).

The line of dip can be ascertained with great accuracy by means of the Dip Circle (§ 125), which is merely a very delicate explorer specially adapted to the purpose, while the intensity can be measured by methods explained in the mathematical parts of the subject; it is then found that both remain practically the same for a considerable distance, say several miles, round any given point; in other words (§ 118), *in any given locality the earth's field is uniform*; we may thus picture to ourselves each locality as mapped out by lines of force parallel to the line of dip.

The direction of the line of dip varies gradually from one locality to another; speaking broadly it may be said that its positive direction—in other words, the positive direction of the earth's lines of force—slopes more or less downwards in the northern hemisphere and upwards in the southern, though in § 126 a more exact statement will be found on this point.

122. Magnetic Meridian. Declination and Inclination. Horizontal and Vertical Intensities. Direction of Compass Needle. If at a given place we set up a thin freely suspended magnetic needle it will, as we have seen, set itself along the line of the earth's resultant force at that place, that is the line of dip. Imagine now a vertical plane drawn through this line; this plane is called the *magnetic meridian of the place*. It in general does not coincide with the geographical meridian, and therefore does not pass through the geographical north or south pole. The angle between the magnetic and geographical meridians at any place is called the *magnetic declination* or simply the *declination* at that place.

Now in fig. 77 let A denote some place, and A I the (positive direction of the) line of dip sloping downwards towards the north, so that the north is on the right in the figure. The plane of the paper clearly coincides with the magnetic meridian. Through A draw A H

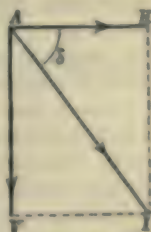


Fig. 77.

horizontally towards the north and $A V$ vertically downwards ; then the angle $H A I$ is called the *dip* or *inclination* at the place A .

Take any length, $A I$, to represent the resultant intensity of the earth's field at A , and complete the parallelogram $V A H I$. Then by the parallelogram of forces the force $A I$ is equivalent to two others represented in magnitude and direction by $A H$ and $A V$ respectively. Of these the former acts vertically downwards and the latter horizontally northwards ; they are called the *vertical* and *horizontal components* respectively of the earth's force, or simply the earth's *vertical and horizontal intensities*. Now, it is clear from the figure that though $A H$ is northwards it is not directly towards the geographical north, for $A H$ is in the magnetic meridian, which (see above) does not pass through the geographical north pole. The direction of $A H$ is called *magnetic north*. Moreover, it is evident by geometry that the angle between $A H$ and the geographical north line is the same as that between the two meridians—that is, it is the declination ; in fact, the two north lines are simply the traces of their respective meridians on the horizontal plane through A .

Now what is the practical significance of the magnetic north line ? If we take a magnetic needle mounted in such a way that it is free to obey the horizontal component of the earth's force *only*, it will clearly set along $A H$ with its north pole to the right. This is precisely what a compass needle is designed to effect. In making a compass needle, the agate or brass cup on which it turns is placed not exactly at its centre of gravity, but (for places in the northern hemisphere) a little nearer its north pole, so that the weight of the needle may just counteract the vertical component of the earth's force, leaving it subject to the horizontal component and that alone. The magnetic north line at any place is therefore the direction in which a compass needle at that place sets itself ; in other words, *a compass needle sets itself horizontally in the magnetic meridian*. It therefore does not point *true* (i.e., geographical) north, but *magnetic north*. Moreover, it is clear that the angle between the needle and the true north line is coincident with the declination ; in fact, the declination is sometimes *defined* in this way.

The two meridians at any place cut the earth's surface in two great circles called *meridian lines*¹ ; evidently the two north lines are

¹ These lines are themselves frequently called "meridians," but it is best to employ the latter term to denote the *planes*.

tangents to the respective meridian lines, and the angle between the latter is coincident with the declination.

It should be noticed that strictly speaking it is the *magnetic axis* (§ 119) of the needle that sets itself either in the line of dip or horizontally in the magnetic meridian according as it is mounted, and for very accurate observations special steps have to be taken for determining that axis.

123. Directivity of Earth's Horizontal Force. Behaviour of Needle under Joint Influence of Earth and Magnet. Since (§ 121) the resultant force of the earth does not appreciably alter either in magnitude or direction over a considerable distance from a given point, the same must be true of its horizontal component; it thus appears that, not only its resultant field, but also its *horizontal field* is uniform in any given locality, and therefore (§ 118) the horizontal field is, like the total field, purely directive.

The directivity of the earth's horizontal force may be shown by the following simple experiment. Take a broad basin or dish of water, float a flat cork or piece of wood at about the middle of it, and lay thereon a magnetic needle. The cork will *turn round* so that the needle sets itself in the magnetic meridian, but it will not *move on*. This it does in obedience to the earth's horizontal force. If now a bar magnet be held with one of its poles at the edge of the basin the cork will travel across the water up to it, the force of the magnet being *not* simply directive.

When a compass needle is balanced on a pivot and a magnet is held near it, the pivot of course prevents translatory movement, and only the directive action of the magnet is operative. For simplicity consider the arrangement in fig. 78: A B is the magnetic north-south line, A being north-



Fig. 78.

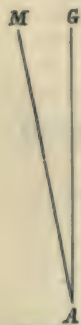
wards, and *ns* a compass needle balanced on a pivot, O; then under the earth's influence alone it sets in the direction *ns*, coincident with A B. Now let a bar magnet S N be placed as

shown, its magnetic axis being perpendicular to AB (i.e., running magnetic east and west) and passing through O . The effect of this magnet alone would be to pull the needle round, making n point towards S . What really happens is that the needle assumes an intermediate position, $n's'$, in which the influences of the earth and magnet just balance one another. Clearly, the nearer the magnet is to the needle the greater will be its influence compared with that of the earth and the greater will be the angle nOn' : indeed, when the magnet comes very near, the influence of the earth is relatively negligible, and the needle points practically due magnetic east.

The student should here be cautioned against a very common error arising from ignorance of mechanical principles, *viz.*, that of supposing that the magnet must exert a certain force before the needle can *begin* to move away from the line AB ; apart from friction on the pivot, which may be neglected, this is certainly not the case—the very least force will deflect the needle, though the deflection may not be noticeable without some delicate means of detection.

EXERCISES:—1. How will the needle behave if the magnet be set along the line AB (fig. 78), (1) with its N pole pointing to the S pole of the needle, (2) with its N pole pointing to the N pole of the needle?

2. (1902.) A short bar magnet is laid on a table with its north pole pointing due north (magnetic). A small pivoted compass needle is placed on the table at some distance due east (magnetic) of the centre of the magnet, and is then moved up slowly to it in a straight line. Describe its behaviour as it approaches the magnet.



3. (1900.) Describe and explain the movement of a small compass needle placed in the middle of a horizontal circle round which the north pole of a long vertical magnet is carried, which produces at the centre of the circle a magnetic field less strong than that of the earth.

124. Details respecting Declination and Inclination. Mariners' Compass and Magnetic Charts.

In fig. 79 let A denote any place in either hemisphere, AG the geographical and AM the magnetic north line, so that the angle MAG is the declination at the place. The declination is termed west or east according

Fig. 79.

as A M lies on the west or east side of A G, the figure shows it west.

The value of the declination is different at different places, and even for the same place changes slowly with the lapse of time. At London in the present year (1903) it is 16° W., and is decreasing at the rate of about $2'$ per year; the earliest record is for the year 1580, when it was $11^{\circ} 17'$ east, it then grew less until in 1657 it was *nil*, after this it became west and increased until it attained a maximum of $24^{\circ} 30'$ in 1816; it is now going back, and will presumably again become *nil* in 1975, after which it will become east, and so on, thus going through its complete cycle of changes in about 636 years, with an *average* rate of about $2'$ per year. An accurate knowledge of the declination at different parts of the earth's surface is of great importance in navigation. The direction in which a ship is going is determined by means of the *Mariner's Compass*, this is essentially a compass-needle fixed to a sheet of cardboard, aluminium, or other non-magnetic material, and having marked on it the cardinal points, N, S, E, W, and numerous intermediate points, the N point coinciding with the north pole of the needle. The latter, therefore, always points *magnetic* north. To ascertain the true direction a correction must be applied for declination, the amount of which depends upon the locality, and for this purpose it is usual to employ *magnetic charts* drawn up on the principle of fig. 82 to be subsequently explained, so as to give the declination as soon as the latitude and longitude are known.

The value of the dip is different at different places. It is usual to name it "north" or "south" according as the north or south pole of the freely suspended needle points downwards, so that (cf. § 121) broadly it is N in the northern and S in the southern hemisphere.¹ Broadly, too, it increases as we travel north or south from the equator. It also changes slowly with time. At London this year (1903) its value is $67^{\circ} 12'$, and is decreasing at the rate of about $1\frac{1}{2}'$ per year; its maximum value was $74^{\circ} 52'$ in the year 1720, but we have no record of its minimum value, so that its cyclic period and average rate of change are unknown.

It is usual to denote the total intensity by I and the horizontal intensity by H. Both these depend upon the place but follow no simple law; broadly, however, we may say that I increases and H diminishes as we travel north or south from the equator. Both I and H are also subject to slight changes with time. The annexed table gives the approximate values of the declination, inclination, total intensity, and horizontal

¹ Some writers speak of the dip as *positive* when the north pole points down, and *negative* when up.

intensity at the places mentioned for the year 1903, the figures under the two latter heads representing dynes per unit pole (§ 111):—

Locality.	Declination.	Inclination or dip.	Total In- tensity, I.	Horizontal, Intensity H.
Boothia Felix	Indeterminate.	90°N.	·65	Nil.
Lerwick	19°W.	72°20'N.	·475	·147
Petersburg	Nil.	70°N.	·48	·164
Edinburgh	19°17'W.	70°20'N.	·485	·162
Newcastle-on-Tyne	18°W.	69°30'N.	·481	·167
Manchester	17°45'W.	69°N.	·480	·172
London	16°W.	67°12'N.	·470	·181
Paris	15°30'W.	65°30'N.	·47	·191
New York	7°50'W.	72°N.	·61	·193
Mexico	8°E.	45°N.	·48	·337
Cape Town	30°W.	56°S.	·36	·216
Sydney	9°E.	62°S.	·57	·313

125. The Dipping Needle and Dip Circle. In determining the line of dip practically it is somewhat inconvenient to employ a *freely* suspended magnetic needle. The best instrument for the purpose is the *dip circle* (fig. 80). It consists of a vertical graduated circle with a horizontal axis at its centre, and perpendicular to its plane. On this axis turns the magnetic needle used for determining the dip, and termed the *dipping needle*; the axis should pass accurately through its centre of gravity, and the mounting be such as to diminish friction on the bearings as much as possible. The vertical circle and needle are mounted as shown on a frame, so that they can be turned bodily about a vertical axis on a horizontal graduated circle which is fixed. The instrument is further provided with levelling screws and a spirit level, and care must be taken in using it that the horizontal circle is levelled properly.¹ Suppose now the instrument used at a place in the northern hemisphere. Let the plane of the paper represent the magnetic meridian, the north being on the left hand; then the figure shows the position assumed by the needle *when the plane of the vertical circle is in the magnetic*

¹ There are many other details to be attended to in order to ensure great accuracy in the result, especially, as respects, determining the magnetic axis of the needle; these we intentionally omit.

meridian, and the point to be noticed is that it then sets in precisely the same way as if it were *freely suspended*. For the mode of mounting only precludes its tilting *perpendicular* to the plane of the vertical circle, and as the earth's resultant force is entirely *in* that plane, the mounting in no way impedes the needle's fully obeying it. Thus it sets along the line of dip, and the dip itself is read off on the vertical circle.

But what is the use of the horizontal circle? Well, if we knew beforehand the exact direction of the magnetic meridian, we could dispense with it. But of that direction we are in general ignorant, and the horizontal circle enables us to find it. To understand how, let us imagine the



Fig. 50.

vertical circle set in a plane *perpendicular* to the magnetic meridian. The horizontal component of the earth's force being then *in* the plane of the meridian simply tends to tilt the needle perpendicular to the plane of the circle, and this it cannot do by reason of the way it is mounted; this part of the force is therefore quite inoperative. But the *vertical* component tends to pull the needle into a vertical position, and to this the mounting offers no impediment. *Accordingly the needle then sets vertically*. But it will not set vertically if the vertical circle be in *any other* plane: what we do then is to begin by turning the upper framework of the instrument until the needle sets at the reading 90° , we then know that the plane of the vertical circle is perpendicular to the magnetic meridian, and all we have then to do is to turn it through 90° of the horizontal circle when we know it is in

that meridian, and we can proceed to read the dip as hereinbefore explained.

EXERCISES :—1. (1902.) An unmagnetised needle is suspended by a fine thread through a small hole at its centre and is balanced so as to hang freely in a horizontal position. What change in the position taken by the needle will occur if it is magnetised and then suspended as before ?

2. (1901.) Explain why the inclination of a dip needle at any place is less when the needle swings in the magnetic meridian than when it swings at right angles to the same.

126. Isoclinic Lines. Earth's Magnetic Equator and Magnetic Hemispheres. If the student will examine fig. 81 he will perceive that it is a map of the world with the usual parallels of latitude and longitude, and also a number of somewhat irregular curved lines. These are called *isoclinic lines*, and their meaning is that *at all places on any assigned one of them the magnetic inclination is the same*. The value of the inclination in degrees is (approximately) represented by numbers attached to the several lines: thus a line marked 70 runs through Central Asia, North Russia, the Midland Counties of England, the Atlantic, and the Central States of America; the inclination at all places on this line is (about) 70°. All along the isoclinic line marked 0 the inclination is *nil*, the dipping-needle setting horizontally; this particular line is called the *aclinic line* or magnetic equator. The magnetic equator does not coincide with the geographical equator, being considerably north of it over Africa and Asia, and south of it over America. It is strictly the *magnetic* and not the geographical equator that divides places where the dip is north (§ 124) from those where it is south. The regions north and south of the magnetic equator are conveniently termed the N. and S. *magnetic hemispheres*; the true canon (cf. § 121) is therefore that the dip is N. at places in the N. *magnetic hemisphere* and S. at places in the S. *magnetic hemisphere*.

There is a certain spot in the far north of America (lat. 70° 5' N., long. 96° 46') known as Boothia Felix; and in the year 1831 Sir J. C. Ross discovered that here the dipping-needle sets vertically—that is, the inclination is 90°. This place is called the *North Magnetic Pole of the Earth*; it is about 1200 miles from the Geographical North Pole.¹ Analogy suggests that there must be a similar South Magnetic Pole

¹ The North Magnetic Pole of the Earth is primarily defined as the place where the dipping-needle sets vertically with its north pole downwards. In 1831 it was at Boothia Felix; it may have shifted slightly since then.

somewhere in the southern hemisphere, but hitherto it has not been discovered.

127. Isogonic Lines. The curves shown in fig. 82 are called *isogonic lines*, and their meaning is that at all places on any assigned one of them the magnetic *declination* is the same. It will be observed that a great number of them pass through the north magnetic pole, and that they are very irregular. At places on the isogonics marked 0 the declination is *nil*; these particular lines are called *agonic lines*. There are three of these agonics: the first passes from Boothia Felix through Canada, the Eastern States, and Brazil; the second through Finland, St. Petersburg,¹ Central Russia, Persia, the Indian Ocean, and Western Australia; while the third is an oval covering Japan and a part of Siberia and China. At places between the first and second the declination is W., between the second and third it is E., within the third it is W., and eastward from the third round to the first it is again E. There is a very small agonic area in the South Pacific within the oval marked 5 in the figure. The numbers attached to the several lines show the (approximate) declinations along them.² Of course, at the magnetic pole (Boothia Felix), *H* is *nil*, and there is therefore no force tending to move a compass-needle, and such a needle will point any way we please to set it, that is, the declination is *indeterminate* (cf. table § 124).

EXERCISE:—Where is the earth's *vertical* intensity *nil*?

128. Elementary Representation of the Earth's Magnetism. If we take a long, thin bar magnet (fig. 71, p. 131), and hold an explorer directly in front of S, it will set itself along the magnetic axis B S N A, with its N pole towards S. If now we carry it along the line S U T V N it will at all places point as shown by the arrows; between S and T the north pole will incline downwards, at T the needle will be horizontal, and between T and N the north pole will incline upwards, until at N the north pole will again point along the magnetic axis. This is very similar to the behaviour of a dipping-needle when carried from Boothia Felix across the magnetic equator and southwards. A better mode of representing the earth's magnetic

¹ In the figure this line is drawn too far east; it looks as if it passed about through Archangel instead of St. Petersburg.

² Both the isoclinics and isogonics change slowly with time; those in the diagrams given are for several years ago.

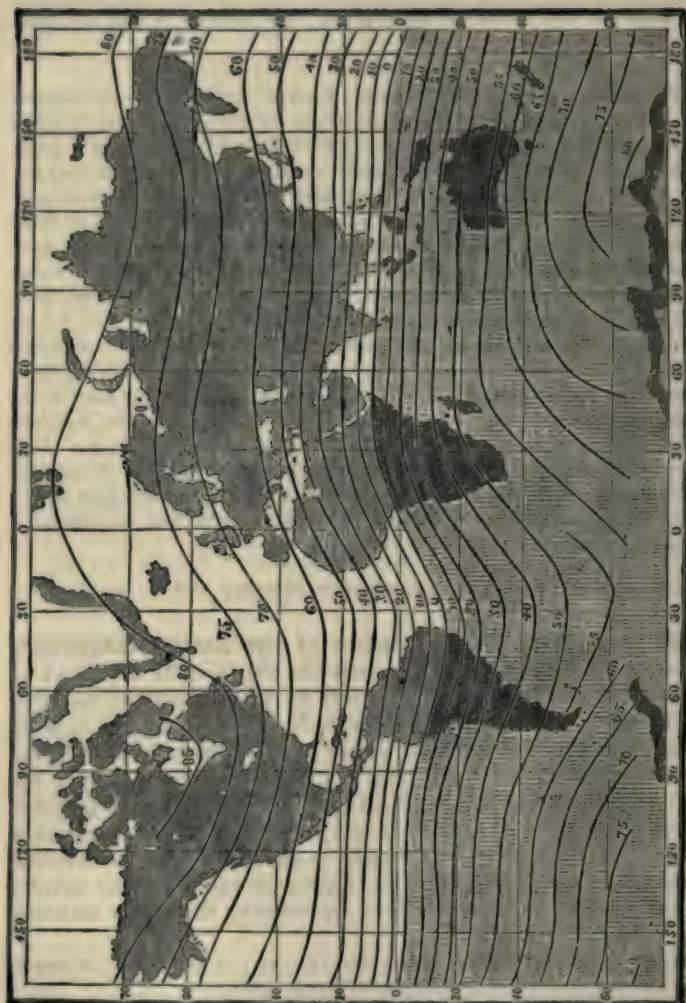


Fig. 81.—ISOCLINIC LINES.



Fig. 82.—Isomeric Lines.

action is shown in fig. 83. We have a large wooden globe, and along one of its diameters is fixed, as shown, a strong bar magnet *con-*

siderably shorter than that diameter. Produce now the magnetic axis to cut the globe in the points B and X, and draw E E' perpendicular to B X through the common centre, C, of the globe and magnet. Then this arrangement *roughly* represents the magnetism of the earth, B corresponding to Boothia Felix and X to the unknown south magnetic pole, while E E' roughly represents the earth's magnetic equator. P, Q, Q', P', represent places in the N and S magnetic hemispheres. In all positions *h h'* represents



Fig. 83.

the horizontal north-south line, *sn* a dipping-needle, and the inclination of *sn* to *h h'* represents the dip. If we actually fix up such a globe, and carry an explorer round from B to X, it will set itself in the several positions shown by *sn*.¹

It should be carefully noted that, in order that the dip at the several points of the model should be approximately equal to the actual dip at corresponding places on the earth, the length of the magnet S N must be suitably adjusted to the diameter of the globe; if not, though the general movements of the explorer will be similar, its dip will be very far wrong except quite near B (and X). And even if the magnet be adjusted as well as possible, the model is still but a rough representation of the earth, many important details of the earth's magnetism being quite unindicated; for example, according to the model, the isoclinic lines should be all parallel circles,

¹ In practice it is best to keep the explorer in one place, and turn the globe so that B, P . . . X come in succession directly below it; the explorer then gradually turns round. This method has the advantage that the line *h h'* always is horizontal, so that it is easier for the eye to follow the movements of the needle.

which we have seen (§ 126) they are not. But for rough elementary purposes, the ideas conveyed by the model are often convenient. Looking then at the globe in fig. 83 as depicting the earth itself, we may for such rough purposes refer its magnetism to an *imaginary internal magnet*, S N. The points S and N (which are a good many miles beneath the earth's surface) may be termed its "representative" magnetic north and south poles respectively; they must not be confused with the points B and X, which we still call the "magnetic poles." And care must be taken not to refer the earth's magnetism to polarity concentrated at B and X.

The line B S N X is termed the *magnetic axis of the earth*, and for elementary purposes it is usual to regard all the magnetic meridians as passing through it; in reality, however, this is a long way from true—e.g., the magnetic meridian of London when produced passes about midway between the geographical and magnetic north pole, thus falling short of the latter by about 600 miles.

It should be observed that the errors involved in these elementary views are more serious in the southern than in the northern hemisphere; indeed, it is very probable that the south magnetic pole X is a myth, or if there be such a pole there are two of them—that is, two places in the southern hemisphere at which the dipping-needle would set vertically. As a matter of fact, the earth's magnetism is exceedingly complex, and cannot be adequately represented in any simple way.

129. Elementary Representation of Declination.

We have seen (§ 128) how the foregoing elementary view roughly explains *inclination*. We can also make it do the same for *declination*. In fig. 84 the circle represents a plan of the northern hemisphere, G being the geographical and B the magnetic north pole. P is any place, G P its geographical and B P



Fig. 84.

magnetic north pole. P is any place, G P its geographical and B P

its magnetic meridian, the latter being drawn on the assumption (§ 128) that it passes through the magnetic axis. *The angle B P G then represents the declination.* At any point on the line Q B G R the declination is *nil*, so that this is the agonic line.

It is clear that this representation is very inadequate. It makes out that there is only one agonic line, which is a great circle of the earth; this (cf. § 127) is by no means true. It further makes out that as we travel northwards along a given geographical meridian, the declination in general increases; this again, though true in some regions—*e.g.*, the North Atlantic—is not true in others, *e.g.*, Eastern Siberia (cf. fig. 82).

EXERCISE:—Show that there are certain localities at which the north pole of a compass-needle points (geographical) south, east, and west respectively.

130. Inductive Action of the Earth's Field. If at any place we hold a straight iron or steel bar along the line of dip, the lines of force of the earth's field will enter it at one end and leave it at the other, and by the law in § 110, the end at which they leave it acquires northern polarity; in other words, *the end pointing in the positive direction of the line of dip becomes a north pole*; in the north magnetic hemisphere (§ 126) this is the lower end, in the south the upper, while at the magnetic equator where the dip is *nil*, it is the end pointing northward.

Suppose now that instead of holding the bar along the line of dip, we set it magnetic north and south. To understand what happens, let us resolve the earth's force into its horizontal and vertical components. The former magnetises the bar, so that the end pointing northwards becomes a north pole. The latter tends to produce side magnetisation, after the fashion indicated in fig. 48, p. 108. But, as was explained in § 116, the latter effect is very feeble, and may be disregarded. The magnetisation is therefore practically that due to the horizontal intensity only, and must clearly be weaker than when the bar is held in the line of dip.

In like manner, if the bar is set vertically, the magnetisation is that due to the vertical component of the earth's force only; the lower end of the bar becomes a north pole at places in the northern magnetic hemisphere, and *vice versa* in the southern. On the magnetic equator the vertical force is *nil*, and a bar held vertically is unaffected.

If the bar be held perpendicular to the line of dip¹ the component of the earth's force in the direction of its length is *nil*, and it is quite unaffected (except for a negligible side action). In fine, in whatever direction it be held it experiences simply the effect of the component of the earth's force *in that direction*.

Any and all of these effects can readily be shown with a long, soft iron bar. For example, if such a bar be set vertically (say in London), and a compass-needle be held near its lower end, the north pole of the needle is repelled, while when placed near its upper end, the south pole is repelled. If the bar be now gradually tilted away from the line of dip, these effects grow weaker until, when nearly perpendicular to that line, the ends of the bar attract either pole of the needle indifferently, the action now being simply due to the inductive effect of the needle itself (§ 86). In order that these experiments should be successful, the bar should be of *very soft* iron, otherwise the earth's field is too weak to produce a good effect. The compass-needle should also be weak, otherwise its inductive action on the bar may overcome that of the earth (§ 87).

A hard iron or steel bar may be magnetised by the earth's inductive action, provided it be held in a suitable position and hammered so as momentarily to weaken its molecular rigidity (cf. § 102). Thus, if a common poker be held N. and S., and struck sharply on the handle a dozen times or so, it will, on removing and testing, be found magnetised. If it be now turned the other way round and again struck, its magnetism may be reversed or neutralised, though it is difficult to know how much to strike to secure *exact* neutralisation.

It not unfrequently happens that iron rods are found magnetised when we want them to be perfectly neutral. A good way to neutralise them is as follows:—Set up a compass-needle so as to determine very nearly the direction of the magnetic meridian, make a chalk-line on the table in this direction and take the needle away. Then hold the bar firmly in a direction as nearly as possible perpendicular to the chalk-line, and hammer it at one end. This loosens the molecules, and there being in this position of the bar no independent field which can appreciably influence them, they simply (§ 95) turn

¹ Whether in the magnetic meridian, or perpendicular to it, or otherwise, is immaterial.

round in obedience to each other's mutual attractions and form closed magnetic chains.

The student should examine fig. 85, which shows the effect of introducing a bar of iron lengthways (*i.e.*, along the lines of force) into the earth's or any other uniform field (§ 118). Prior to its introduction the lines of force of the field are all straight and parallel, and their positive direction is supposed to be downwards, though the artist has forgotten to mark in the arrows. On inserting the bar it acquires polarity in accordance with the law of § 110, while on account of its high permeability the lines become distorted as

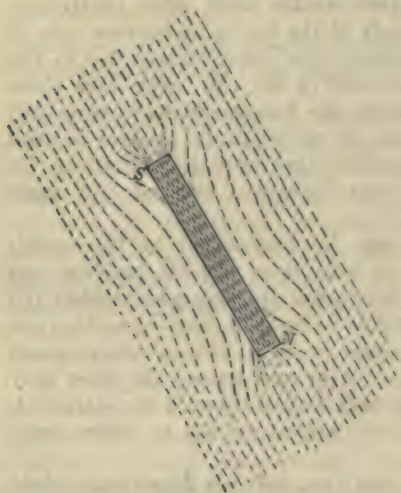


Fig. 85.

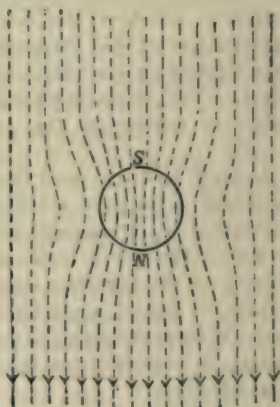


Fig. 86.

shown, the field within the bar becoming very dense. Fig. 86 shows the effect of setting the bar *across* the field, the letters N and S indicating the feeble side polarity.

EXERCISES:—1. (1902.) A long bar of soft iron lies on the table in the magnetic meridian, and the north end of it is slowly raised until the bar is vertical. What changes in magnetism due to the inductive action of the earth does it undergo?

2. (1900.) How would you place a rod of soft iron for it (i.) not to

be magnetised, (ii.) to be magnetised as much as possible, by the earth's inductive action? Give your reasons.

3. (1899.) When a rod of soft iron a yard long is held in a vertical position, each end when held downwards attracts one pole of a compass-needle and repels the other; but when the rod is held horizontally, and in a certain direction, both ends attract both poles of the needle. Explain these facts.

4. (1903.) A tall iron mast is just forward of the compass of a wooden ship. Explain how this will affect the direction of the compass when the ship is sailing (i.) to the east, (ii.) to the north, in the northern hemisphere.

131. Astatic and other Compound Magnetic Needles. It is sometimes necessary in physical experiments to have a magnetic needle upon which the earth can exert no influence; such a needle is called *astatic*. It is not possible to make a *single* needle which shall be astatic, but by combining two needles as shown in fig. 87 the desired property is secured. The two needles must be exactly similar in length, strength, etc., and are firmly fixed on a common axis of brass or aluminium with their poles in opposite directions. Suppose now such a combination suspended by a fine thread attached to a hook, and set so that the vertical plane through their magnetic axis makes any angle with the magnetic meridian. The horizontal force of the earth exerts a certain turning effect on the upper needle, tending to make the combination set with its left-hand portion northwards, and also a precisely equal turning effect on the lower needle, tending to make it set with its left-hand portion southwards. These two turning effects neutralise one another, and on the whole the earth has no influence whatever, so that the needle remains in *any position we please to put it*.



Fig. 87.

If the needles be not exactly similar, or be not fixed accurately parallel, the two turning effects will not exactly neutralise each other, and the combination will not be *perfectly* astatic; a needle *nearly* astatic is, however, sufficient for most purposes for which such needles are required (§ 170).

We occasionally require to consider the case of two needles riveted together at their centres, or mounted on a common axis, but *not parallel*

to one another. If the combination be suspended so that the needles are free to turn horizontally, it must evidently (whatever be their relative strengths, lengths, etc.) set itself in such a position that the *turning effects of the earth upon the two needles balance one another*. From this the exact position can in all cases be determined by mechanics, but in the simple case where the needles are *in all respects alike* it is obvious that the position of rest will be that in which the magnetic meridian bisects the angle between them (or more strictly between their magnetic axes), the north poles of both lying on the northern side of the east-west line : the student should draw a figure.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER IV.

1. The earth is to be regarded as a magnet whose *northern* regions possess *southern* polarity, and *vice versa* (§ 120).

2. The direction of the earth's resultant force at any place is called the *line of dip*, and is indicated by a freely suspended needle or by the dip circle. The earth's field in a given locality is uniform, and the positive direction of its lines of force slopes downwards in the northern *magnetic* hemisphere and upwards in the *southern* (§§ 121, 126).

3. The vertical plane through the line of dip is called the *magnetic meridian* of the place, and does not in general coincide with the geographical meridian. A straight line drawn horizontally in the plane of the magnetic meridian constitutes the *magnetic* north-south line at the place, and it is along this that the compass-needle sets. The angle between the magnetic north-south line and the geographical north-south line is called the *declination* of the place, and that between the magnetic north-south line and the line of dip the *inclination* or *dip* of the place. The declination is east at some places and west at others, and the dip is "north" or "south" according as the place is in the northern or southern hemisphere (§§ 122, 124, 126).

4. The intensity at any point of the earth's field may be resolved into two components, one horizontal and one vertical ; it is the horizontal component alone which affects a compass needle (§ 122).

5. Experimental proof of the directivity of the earth's *horizontal* field (§ 123).

When a compass needle is acted on by a magnet the needle takes up a position in which the influence of the earth and magnet balances one another, but (neglecting friction on the pivot) the force of the magnet does

not require to reach a certain value before the needle will *begin* to move (§ 123).

6. The Dip Circle and the method of using it to determine (i) the magnetic meridian, (ii) the dip (§ 125).

7. Elementary representation of dip and declination, and its unsatisfactoriness (§§ 128, 129).

8. Effects of placing an iron bar (i) in the line of dip, (ii) magnetic north and south, (iii) vertically, (iv) perpendicular to the line of dip. Magnetisation and demagnetisation of a steel bar by the help of the earth (§ 130).

9. Astatic needles (§ 131).

EXERCISES ON CHAPTER IV.

1. If you wish to support a uniform bar magnet horizontally on a pivot, how is it that the pivot must be placed nearer to one end than to the other? To which end must it be nearest in this country?

2. How does the position of a "dipping needle" change when it is taken from London (1) toward the north pole, or (2) towards the equator?

3. A small magnet is placed upon a flat cork which floats in basin of water, and it is fastened to the cork with a little wax. Describe and explain the behaviour of the magnet (1) when under the influence of the earth's magnetism alone, (2) when an artificial steel magnet is brought near it.

4. How would you construct an astatic needle out of a uniformly magnetised strip of watch-spring, which you are allowed to bend or break as you please?

5. If a compass were carried round the equator, would it point in the same direction in all places? If not, state as nearly as you can what changes would be observed in its behaviour during the journey.

6. An astatic combination of two magnets are at right angles instead of parallel to each other. If it be suspended as usual, what position will it assume with regard to the magnetic meridian? Illustrate your answer with a diagram showing the forces which act upon the magnets.

7. What is meant by saying that the magnetic dip at London is $67^{\circ} 12'$? State in general terms at what places on the earth's surface the magnetic dip is least.

8. A bar of soft iron, A B, is placed horizontally east and west in London; the east end, A, being about four inches to the west of the north-seeking pole of a compass-needle. The end A being fixed, B is raised until the bar is vertical. How is the needle affected by the bar when in its original and final positions?

9. A large soft iron rod lies on a table in the magnetic meridian, and a dipping needle is placed at some distance and at about the same level, (1) due south, (2) due north of it. How will the magnitude of the angle of the dip be affected in each case? (Neglect any inductive action between the needle and the bar.)

10. A compass needle is deflected 15° from the meridian, when a bar magnet is placed on the table some distance away. Will the deflection be altered if the poles of the magnet are connected by a bent iron rod? Give reasons.

11. A tall iron mast is situated a little in front of a compass in a wooden ship. Explain the nature of the compass error when the ship is sailing in an easterly direction, (1) in the northern, (2) in the southern hemisphere.

12. Given a magnet and the means of suspending it. How will you determine (1) the magnetic meridian, (2) in which direction *north* lies? It is assumed that you do not know which end of your magnet is a north and which a south pole.

13. An iron rod held vertically is tapped with a mallet. The upper end is found to repel the south pole and attract the north pole of a compass needle. The rod is now quickly inverted, and the same end (which is now the lower) is tested again. It is then tapped and once more tested. State what results you would expect and explain them.

14. A horseshoe magnet lies flat on a sheet of brass, which is supported by strings in such a way that it turns about a vertical axis but always remains horizontal. How will it place itself?

15. (1903.) In England a dip needle swinging in a plane perpendicular to magnetic meridian returns to a vertical position when deflected from it, but does not do so at the magnetic equator. Explain this.

16. A bar magnet is laid on a table perpendicularly to the magnetic meridian, and so as to point to the centre of a compass-needle. Describe and explain the behaviour of the needle.

17. A bar of soft iron is held vertically over the centre of a dip needle, but not near enough to have magnetism induced in it by the needle. Is the dip increased or diminished by the presence of the bar, and would the result be the same in each of the two hemispheres?

18. A strip of steel is bent about the middle point so that the two halves are inclined to each other at a right angle. It is then magnetised, so that its extremities are south poles and the angular point a north pole, and is placed on a flat piece of cork floating in a basin of water. How will it set?

19. A complete circumferentially magnetised steel ring (§ 92) is suspended by a thread so that its plane is vertical. How will it behave under the influence of the earth's magnetism?

20. (1899.) A magnet can rotate in a vertical plane about a horizontal line which lies in the magnetic meridian and joins the centre of the magnet to the centre of a compass needle. Describe the movements of the compass needle as the magnet rotates slowly,

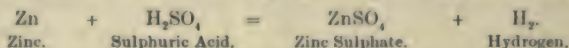
PART III.

VOLTAIC ELECTRICITY OR ELECTRODYNAMICS.

CHAPTER I.

GENERAL FACTS AND PRINCIPLES.

132. Chemical Preliminaries. If we place a piece of common zinc in dilute sulphuric acid, the zinc dissolves and bubbles of hydrogen gas come off which can be ignited; at the same time zinc sulphate is formed which dissolves in the water with which the acid has been mixed. The chemical equation expressing the action is



Moreover the mixture becomes hot during the process.

Now let us briefly regard this from the standpoint of energy (§ 61). The group SO_4 (called *sulphion*), which exists in the sulphuric acid, has a certain chemical affinity for the zinc, and while they are separate they are in a position analogous to that of a weight raised above the earth's surface, or to a piece of coal which is ready to unite with the oxygen of the air; they possess chemical *potential energy* (§ 61), and when they come together forming the compound Zn SO_4 this potential energy is converted into heat. Before however the SO_4 can unite with the Zn , it has to be riven from the H_2 with which as sulphuric acid it is united, and this separation resembles the *lifting* of a weight; work has to be done to effect it, which can only be at the expense of some of the heat in the mixture. The heat consumed in separating the SO_4 from the H_2 is, however, *less* than that produced in its union with the Zn , so that *on the whole* there is a conversion of chemical potential energy into heat, and it is this

total action which is alone of importance. The same thing occurs in a great many other chemical actions.

When any action (chemical or otherwise) results in the conversion of potential into some other form of energy, the action is often spoken of as a *source* of energy though of course (§ 61) no energy is really created; thus the combustion of coal and the action of sulphuric acid on zinc are both "sources" of energy. In the course of this chapter we shall see how the latter and several other chemical actions may be made sources of *electrical energy*—i.e. (§ 62), of energy manifesting itself in association with electricity.

If while the zinc is dissolving in the sulphuric acid we pour mercury upon it, the action ceases, and in like manner if the zinc be first well cleaned and then rubbed with mercury (in which case it is said to be *amalgamated*) the acid under ordinary circumstances has no action upon it. The same is the case if the zinc be perfectly pure; in fact, the commonly received explanation of the action of the mercury is that it dissolves the outer layers of the zinc, leaving the impurities behind, so that the portion in contact with the acid virtually is pure. *Why* there should be this difference in the behaviour of pure and impure zinc will be explained in § 138.

133. Simple Voltaic Cell. Now take a vessel containing dilute sulphuric acid (fig. 88), and in it put a plate of amalgamated zinc, Z. No action whatever occurs. Next put into the acid a plate of copper, C (not touching the zinc). Again no action occurs. Now connect the zinc and copper plates by a copper wire, M, which is most conveniently done by aid of binding screws. Bubbles of hydrogen are then given off from the *copper* plate; and if the action be allowed to go on for some time, it is found that the zinc loses weight while the copper does not, and that the solution contains zinc sulphate. In fact, as soon as metallic connection is established between the two plates, the same chemical action sets in as in § 132: the zinc dissolves, and hydrogen is liberated. *Why* the hydrogen makes its appearance on the copper instead of the zinc is a secondary point, which we shall discuss in § 146.



Fig. 88.

The contrivance in fig. 88 is called a *simple voltaic* or *galvanic*¹ cell. It serves as a convenient introduction to the study of electrodynamics, although in practice it is seldom used, there being other kinds of cells which answer much better. It frequently happens too that a single cell of any kind is insufficient to do what we want, and we then employ a combination of several cells, such combination being termed a *battery*. The most important cells and batteries we shall study in due course, but there are certain general points connected with the whole subject which it is desirable to understand at the outset, and these we shall consider in the remainder of the present chapter. It must be understood that though our remarks may be illustrated by reference to the simple cell, they apply with mere changes of detail to cells and batteries in general and also to dynamos.

In the simple cell we may, in place of a copper plate, employ one of platinum or gas-coke or any substance which is a good conductor of electricity and is not acted on chemically by the acid.

134. Introductory Considerations and Nomenclature. The wire, M joining the plates of a cell (fig. 88) is found to possess several remarkable properties: for example, if held lengthways over a compass-needle it will deflect it from the magnetic meridian. But as soon as it is detached from one of the binding-screws, or cut at any point so as to interpose an air-gap, these properties at once disappear, the chemical action in the cell ceasing at the same time. It is therefore natural to attribute the properties in question to some influence flowing along the wire, but which cannot cross an air-gap, and this influence is called an *electric current*.

Now let us look more fully into the matter:—The first point to notice is that (as we shall show experimentally in § 140) before the plates are connected by the wire they are at different potentials, that of the copper being the higher. This being so, then, by Poisson's Principle (§ 32), as soon as connection is made, electricity flows along the wire *from the copper to the zinc plate, as indicated by the arrows* (fig. 88). According therefore to this view, the so-called electric current is a real flow of electricity, just as truly as a water current in

¹ From Volta and Galvani, two Italian physicists of the eighteenth century.

a pipe is a real flow of water, and cutting the wire at any point, or detaching from one of the plates, corresponds to turning off a cock in the pipe.

This however is not all that takes place in a voltaic cell. If we take two electrostatically charged conductors at different potentials and connect them by a wire, a momentary current flows and the potentials become equalised. But if the conductors be respectively attached to two machines working to different potentials then the potentials cannot become equalised because the machines are always unequalising them; we have in fact in the machines a source of energy (§ 132), and this energy maintains a continual potential difference in the conductors, giving a continual current. It is the same with our cell. The chemical action of the sulphuric acid upon the zinc is a source of energy, it maintains a continual potential difference between the plates, and we have a continuous current so long as the cell is in action.

The current in a voltaic cell does not exist in the wire only, but also in liquid. The electricity having flowed from the copper to the zinc by virtue of the potential difference of the plates, is driven *from the zinc across the liquid to the copper by virtue of the energy of the chemical action*. That is, it flows *down the potential-gradient* through the wire, so to speak "of its own accord," and is then forced *up the gradient* by the energy of the chemical action.¹ Having got up, it is ready to flow down again and so on, so that it keeps on flowing round. The whole cell may be likened to a couple of water tanks at different levels connected by a flow-pipe and a pump. Water flows from the upper tank to the lower "of its own accord," it is then forced up again by the energy of the pump, flows down again, and so on, so that there is a continuous current as long as the pump works.

The entire path of the current through the wire and cell is called the *circuit*, the portion through the wire being the *external circuit* and that through the liquid (including the plates, screws, etc.) the *internal*. Now in the water illustration just given there is a gradual fall in *level* from the upper to the lower tank, but the water *current* is the same at all parts of the circuit, and this is true whether the

¹ In § 138 we shall see that there is not an up-gradient *all the way* from the zinc to the copper through the liquid, but at present this is a detail which does not concern us.

pipes be of uniform bore or not.¹ In like manner in the electric circuit there is a gradual fall of *potential* along the wire from the copper to the zinc, but the electric *current* is the same at all parts of the circuit both external and internal; the student should note this very carefully—a common error is for example to imagine that if the wire is thicker at one end than at the other the current will be stronger at the thin end, but it is *not*, it is just the same all along the wire. Another common though less serious misconception is to look upon a cell as a *generator* of electricity, but it no more makes the electricity than a pump creates water; in fact, voltaic cells, dynamos, and all other so-called “electric generators” are nothing more than *electric pumps*: the electricity is in the circuit already, and all the “generator” does is to pump it round and so make it produce numerous effects which it cannot when at rest.

Frequently the external circuit consists not of a mere wire, but includes some instrument placed in the course of the wire and through which the current is conducted. A mere wire, or any instrument in which no mechanical or chemical action occurs, is called a *dead connexion*, and unless the contrary is stated we shall always suppose our connexions to be dead. The characteristic of a dead connexion is that it *contributes* no energy and that *all the energy it absorbs from the current is converted directly into heat*; in other words it is neither a “source” nor a “sink” of energy. When on the other hand any part of a circuit is a source or a sink it may be termed “alive”; an electromotor such as is used to drive tramcars is “alive”—it absorbs energy which is converted into mechanical work.

The binding screws attached to the plates of any cell are called its *terminals* or *poles*; the plate or pole of higher potential is termed the *positive* or *high-potential* (*H. P.*) plate or pole, and the one of lower the *negative* or *low-potential* (*L. P.*) plate or pole; thus in the simple

¹ By the water current at any point of a pipe is strictly meant the quantity of water which in a given time, say one second, crosses a section of the pipe through that point and perpendicular to its sides. Now in fig. 69, p. 129 (now used with different interpretation), let A B C D be a pipe of varying breadth and P Q, P' Q' any two cross sections, and suppose the water flowing from left to right; then it is obvious that whatever quantity of water enters the portion P Q Q' P' of the pipe through the section P Q, an *equal* quantity must in the same time pass out through the section P' Q'; that is *the currents across the two sections are the same*. Precisely the same reasoning applies to the electric current.

cell the copper is the H. P. or + plate and the terminal thereto attached the H. P. or + pole.¹

A voltaic cell may be regarded as a device for *redirecting the energy of chemical action*. If we merely dissolve zinc in sulphuric acid as in § 132, all the energy of the action goes direct to heat; but if we dissolve it in a voltaic cell this energy, instead of going *direct* to heat, goes *first* to pump electricity from a lower to a higher potential. Mark the words *Redirected*. We do not say that in a voltaic cell the energy *does not* go to heat, but that it does not do so *directly*. If the plates are merely connected by a wire all the original chemical potential energy ultimately goes to heat, part in the liquid and plates, and part in the wire; but it does not do so straight away,—it first pumps up the electricity, conferring energy upon it, and this energy afterwards becomes heat. But we can prevent some of it from becoming heat if instead of joining the plates by a mere wire we connect one of them to one terminal of a small electro-motor and the other to the other; the current then drives the machine, which might in turn be used to run a small model tramcar up an incline; in this way some of the energy of the chemical action is converted, not into heat *at all*, but into the potential energy of the uplifted car.

EXERCISES:—1. A piece of copper and zinc are put side by side in a vessel of dilute sulphuric acid. What takes place *in the vessel* when the copper and zinc are joined by a wire?

2. In the preceding question, if, instead of employing a wire, the copper and zinc plates were made to touch below the surface of the acid, what would happen?

3. Give a drawing of a galvanic cell of copper, zinc, and dilute sulphuric acid, showing in what direction the current passes through a wire connecting the two metals, and also through the acid.

4. A piece of zinc and copper are each carefully weighed; they are then connected by a copper wire, and dipped side by side into dilute sulphuric acid contained in an earthenware jar. After, say, half an hour, the pieces of zinc and copper are taken out, washed, dried, and weighed again. Would the weights be the same as at first? if not, how and why would they differ?

5. A current flows through a copper wire which is thicker at one end than at the other. Is there any difference either (1) in the strength of the current, or (2) in the potential at the two ends of the wire? Explain your answer.

¹ The older writers, for reasons into which we need not enter, were in the habit of calling the copper itself the *negative plate* and the terminal attached to it the *positive pole* but this confusing nomenclature is now abandoned.

135. Resistance ; External and Internal. The substances which permit an electric current to flow along them are, in general, the same as those hitherto termed conductors (§ 8): the terms "conductor" and "insulator" thus apply broadly to the same respective substances in electrodynamics as in electrostatics. But there are two important differences. The first arises from the fact that the electrical pressures with which we have to deal are incomparably smaller in electrodynamics than in electrostatics, so that a substance may be a good electrodynamic insulator which is an electrostatic conductor: this is so with wood, and generally with all substances termed in electrostatics "partial insulators" (§ 13). Pure water, though electrostatically a good conductor, is electrodynamically a very bad one.

The second difference arises from the fact that we are dealing now with electricity *in motion*. Now, in electrostatics we have regarded all good conductors as practically alike—for example an iron ball behaves precisely like a copper one: this, of course, is because the charge is on the external surface, it being *the surrounding dielectric* which regulates the behaviour of the ball (§ 58), and not *its own material*. But electric currents flow *through the actual substance of wires and other conductors*, and in so doing encounter opposition, the amount of which depends upon the material of the conductor as well as its size, etc.; this opposition is called the *resistance* of the conductor. As the current flows round the circuit, it has to encounter the resistance of the wire and of any instruments in the external circuit, and also that of the liquid in the cell. The former constitutes the *external resistance*, the latter the *internal*, the two together making the *total resistance*.

The resistance of a wire depends upon three things—*viz.*, its *length*, its *thickness*, and its *material*. For wires of the same material the resistance is greater the *longer* and *thinner* the wire. The reason for this is tolerably obvious, for the longer the wire the greater the distance through which the electricity has, so to speak, to grind its way; while the thicker it is, the broader is the path it affords to the electricity and therefore the less the resistance—just as a broad pipe offers less resistance to the passage of water than a narrow one. In the higher parts of the subject, methods are devised for the actual measurement of resistances, and it is then found that there is a definite law—*viz.*, that for wires of the same material the resistance is *directly* proportional to their length and *inversely* proportional to

the area of their cross section ; thus if we had two copper wires of the same length but of which one had four times the sectional area of the other, the thick one would have only a quarter the resistance of the thin one.

If we consider wires all of the same length and sectional area their resistances vary greatly according to their material. The numbers expressing the relative resistances of wires of different materials, but of the same length and thickness, are called the *specific resistances of the materials* ;¹ their values depend simply upon the materials, and in no way upon the actual lengths, etc. Of all substances, silver has the lowest specific resistance, that of copper is a little greater, that of iron and platinum much greater, and that of German silver greater still. The resistance of insulators is, of course, enormous. Pure water has a very high resistance, but the resistance of dilute sulphuric acid, and of the other liquids employed in voltaic cells, is in general fairly small.

The following numbers represent approximately the specific resistances of the most important metals, that of silver being taken as unity : it should be observed, however, that the numbers vary considerably in different specimens of the same metal, according to purity and the way the wire has been drawn. In some specially prepared copper wires the specific resistance is *less* than that of silver.

Silver	.	.	.	1		Iron	.	.	.	6
Copper	.	.	.	1.1		German Silver	.	.	.	13
Platinum	.	.	.	5.5		Mercury	.	.	.	62.5

Suppose now we compare the resistances of several cells all of the same *kind*, and differing only as respects the distances of their plates apart, and the areas of them below the surface of the liquid. The passage of the current through the liquid from one plate to the other is analogous to its flow along a wire, the distance between the plates corresponding to the length of the wire, and their immersed area to the sectional area of the wire ; hence *the resistance of a cell will be greater the greater the distance between the plates, and the less their immersed area*, or, speaking broadly, *the internal resistance is less the larger the cell*. As will be more fully seen in § 138, the effect of

¹ The term specific resistance receives a more precise definition in the mathematical parts of the subject.

resistance, other things being the same, is to weaken the current, it is therefore in general an advantage to employ cells as large as possible and with their plates as close together as possible.

When the poles of a cell (or battery) are not connected by a wire or conductor it is said to be an *open circuit*; the external resistance is then practically infinite and the current *nil*. If they are so connected the circuit is said to be *closed* or “made” or “complete.” If they are connected by a thick and fairly short wire, whose resistance is practically *nil*, the cell is said to be on *short circuit*, in which case the current is as great as the cell can possibly yield.

In experimental work it is usually necessary to pass the current through some instrument, into which it is conducted by so-called *leads* or *feeders*. These are stout copper wires, which, having very small resistance, do not appreciably weaken the current; a convenient size is No. 18 Birmingham Wire Gauge (B.W.G.), which is about $\frac{1}{16}$ inch diameter.

The main body of the earth is an excellent conductor, electro-dynamically as well as electrostatically. If we connect one pole of a cell to the gas-pipe and the other to the water-pipe, the circuit will be completed through the earth, and the current will flow just as if the two poles were joined by a single wire. In telegraphic work the circuit is commonly completed “through earth,” thus saving the expense of a “return wire,” and also diminishing resistance, since the resistance of the earth portion of the circuit is very small.

EXERCISE :—There are two wires, A and B, of the same material, but of which B is 12 times as long as A and double its diameter. Compare their resistance.

136. Ohm's Law. The Volt, Ohm, and Ampère. Potential Drop. In fig. 89 let A and B be any two points on an electric



Fig. 89.

circuit, and suppose the current flowing along the circuit in the direction of the arrow, so that by Poisson's Principle the potential at A is higher than that at B. Then confining our attention to the portion A B of the circuit,

there are three things which we have to consider, *viz.* :—

- (1) The *current* in it: this we denote by *C*.
- (2) The *potential-difference* (*P.D.*) of its extremities A and B: this we denote by *V*.

(3) Its *resistance* : this we denote by R .

Now there is a law known as *Ohm's Law*,¹ which connects these quantities, and is to the effect that on the understanding that each is estimated in its own proper units to be immediately explained, then

$$C = \frac{V}{R} \quad \dots \quad (1)$$

or putting it in words :—

$$\begin{array}{l} \text{Current} \\ \text{in any portion of a circuit} \end{array} = \frac{\text{P.D. of extremities of that portion}}{\text{Resistance of that portion}} \quad \dots \quad (2)$$

In employing this law it is to be understood that potential-differences are to be estimated in units called *volts*, resistances in units called *ohms*, and currents in units called *amperes*. These units are in perpetual use by electricians, and a student soon becomes as familiar with them as he is with the foot as the unit of length, or the pound as the unit of weight. It is quite impossible and also quite unnecessary to give strictly scientific definitions of them in an elementary course ; but the following practical definitions may be helpful :

A *volt* is $\frac{1}{10}$ the Electromotive Force of a Daniell cell. [This definition will be better understood after reading §§ 137 and 148.]

An *ohm* is the resistance of 85 yards of No. 18 B.W.G. pure copper wire (see last par. but one of § 135).

An *ampère* is the current which a volt would drive through an ohm ; that is, if we had a piece of wire of 1 ohm resistance and maintained a P.D. of 1 volt at its ends, the current in it would be 1 ampère.

The P.D. between any two points such as A, B, fig. 89, of a circuit is spoken of by practical electricians as the *potential-drop* along A B ; we may accordingly write Ohm's law in the form—

$$\text{Current} = \frac{\text{Drop}}{\text{Resistance}} \quad \dots \quad (3)$$

$$\text{or} \quad \text{Drop} = \text{Current} \times \text{Resistance} \quad \dots \quad (4)$$

Ohm's Law is the fundamental law of Electrodynamics, and should be thoroughly grasped by the student ; it must, however, be observed that in the forms above given it is only true when the portion of the circuit considered is "dead" (§ 134)—if it contains any source or sink of energy the statement of the law needs modification.

¹ The *proof* of the law is given in the higher parts of the subject.

EXERCISES:—1. A piece of wire has a resistance of 6 ohms, and the P.D. of its ends is 18 volts; what is the current in it?

2. The terminals of an incandescent electric lamp have a P.D. of 50 volts, and it takes a current of $\frac{3}{4}$ ampère; what is its resistance?

3. An over-head trolley-wire has a resistance of half an ohm per mile, and carries a current of 20 ampères; find the potential-drop per quarter-mile along it.

137. Electromotive Force. An extremely important quantity in connexion with a cell or battery is what is called its *Electromotive Force* (*E.M.F.*). This may be roughly defined as “the influence which drives the current,” but its strict definition is *the difference of potentials of its terminals when on open circuit*.

Now it is found by measurement (§ 140) that the E.M.F. of a cell, *when freshly fitted up and in good condition*, depends simply upon the *kind* of cell—i.e., whether it be a simple cell or a Daniell, Leclanché, Poggendorf, etc. (Chap. II.); it in no way depends upon the *size* of the cell or the arrangement of its plates: the student should note this carefully and contrast it with what was said in § 135 regarding internal resistance. It is thus possible to tabulate the E.M.F.’s of the different types of cell in definite numbers. A Daniell cell (§ 148), for example, has an E.M.F. of 1·1 volt, and this furnishes the practical definition of the volt given in the preceding article.¹

The *difference* of potentials of the terminals of a cell (on open circuit) is a perfectly definite thing depending only on the kind of cell, but their *individual* potentials are, so to speak, more or less accidental. Thus, if we have a Daniell cell with its terminals insulated from the earth, we know their P.D. is 1·1 volt, but we have no guarantee as to potential of either of them separately. But suppose we earth the L.P. or – terminal (§ 134), thus rendering its potential zero, then the potential of the H.P. or + terminal becomes 1·1 volt; while if we earth the H.P. terminal the potential of the

¹ Strictly, the expression “kind” of cell must be taken to include the *quality* of the materials employed in its construction—i.e., the purity of the plates, and more particularly the purity and strength of the acid or other exciting material. Thus the E.M.F. of a Daniell cell in which the plates are *pure* zinc and copper, and the solutions are pure zinc sulphate and pure copper sulphate *of equal density*, is 1·1 volt, and this is the kind of cell referred to in defining the volt in § 136. For other forms of Daniell the E.M.F. may vary from about 1·05 to 1·15 volt.

L.P. one becomes = 1.1 volt. If we earth *both* terminals the cell is no longer on open circuit, and the state of affairs is altogether different.

If we earth the L.P. terminal of a cell and connect its H.P. terminal to an insulated conductor—*e.g.*, a brass ball—the latter receives a + electrostatic charge (though exceedingly feeble) in accordance with Poisson's Principle; but unlike the corresponding case in § 32, the potential does not fall during the process, because the chemical action within the cell keeps it up to its standard value; thus in the case of a Daniell cell the ball would require a potential of 1.1 volt. In like manner if the H.P. terminal were earthed and the L.P. connected with the ball, the latter would acquire a negative charge and a potential of -1.1 volt—*i.e.*, 1.1 volt below the potential of the earth.

138. Distinction between Electromotive Force and Terminal Potential-difference. More Complete Theory of the Voltaic Cell. Application of Ohm's Law to the External, Internal, and Complete Circuit. The E.M.F. of a cell is defined (§ 137) as its terminal potential-difference (T.P.D.) *on open circuit*. But it is found by experiment (§ 140) that the T.P.D. *on closed circuit* is *less* than the E.M.F., and, moreover, depends on the resistance of the wire used to connect the terminals being less the less the resistance of the wire. Now let us look into this point, and in so doing we shall learn a good deal more of the action of the voltaic cell—

In § 134 we have said that the chemical action in a cell pumps the electricity up the potential-gradient through the liquid from the zinc to the copper. But this statement is somewhat inadequate, inasmuch as it gives the impression that there is a *gradual* up-gradient, which there is reason to believe is not the case. A nearer approach to the true condition of things will be gathered from fig. 90. No. 1 represents the cell on open circuit. Some action, into whose nature we need not enter, takes place between the sulphuric acid and the amalgamated zinc, this action being confined to a very narrow region lying between the plate and a layer A B.¹ The effect is to establish a difference of potential between the zinc plate and the liquid layer A B, so that, again for a reason into which we need not

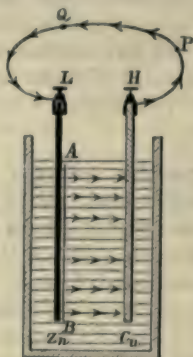
¹ In reality the action occurs on both sides of the plate, but we have taken only one for simplicity.

enter, Poisson's Principle does not apply to this narrow region.¹ But it applies to all the rest of the circuit, so that the potential of the liquid from A B towards and including the copper is the same throughout, and there is no gradient anywhere except from the zinc to the layer A B, where there is steep jump-up equal to the E.M.F.

We next connect the plates by a wire (No. 2). Electricity flows through the wire from H to L, which lowers the potential of the copper. This establishes a down-gradient from A B across the liquid



No. 1.



No. 2.

Fig. 90.

towards the copper, and electricity flows through the liquid down this gradient. The tendency of this flow is to lower the potential of A B and raise that of the zinc plate. But now chemical action sets in between the zinc and sulphuric acid, the effect of which is to maintain a P.D. between the zinc and A B equal to the original E.M.F. Thus *throughout the whole action the P.D. between the zinc and the layer A B remains equal to the E.M.F.* But since there is now a down-gradient from A B through the liquid to the copper, it is obvious that the potential of the copper cannot be so high as that of the layer A B; in other words, *the T.P.D. of the cell on closed circuit must be less than its E.M.F.*

¹ Lest this should look like a violation of the generality of Poisson's Principle (§ 32), it may be pointed out that this region appears to be in a state of electric strain, and in certain respects to resemble an insulator rather than a conductor.

Following the course of the current in No. 2, the electricity starts at A B, the top of the gradient, flows across the liquid to the copper plate where it is part of the way down, and thence continues its course through the wire to the zinc plate which is at the bottom. All this part of the circuit is "dead" (§ 134); the "live" part is the narrow region between the zinc and A B, where the chemical action is going on. As soon as the electricity arrives at the bottom of the gradient (*i.e.*, at the zinc) the energy of this live portion pumps it up to the top (*i.e.*, to A B), whence it runs down again, and so on. If the circuit be broken the chemical action and the current simultaneously stop, and everything returns to the condition of No. 1.

The internal resistance of the cell is that of the liquid between A B and the copper plate, and the external resistance is that of the wire; these together make up the total resistance, and it is this which the current has to overcome in the course of its flow from the top to the bottom of the gradient.¹

What may be called the "driving influence" for the *complete* circuit is the P.D. between A B and the zinc—*i.e.*, the E.M.F.—and this has to overcome the *total* resistance; the driving influence for the *external circuit alone* is the T.P.D., which has to overcome the external resistance; and the driving influence for the *internal circuit alone* is the P.D. between A B and the copper plate—*i.e.* (§ 136) the *potential drop across the cell*; this is usually termed the *internal drop*, and is obviously the excess of the E.M.F. over the T.P.D. Electrical engineers frequently speak of the internal drop as the "lost volts," from the fact that they are spent in driving the current against the internal resistance and are not available for external work.

Let us now, bearing in mind (§ 134) that the current is the same throughout the entire circuit, apply Ohm's law to its different parts: The P.D. of the extremities of the *complete* circuit is the E.M.F., hence by equation 2, § 136, we have—

$$\text{Current} = \frac{\text{E.M.F.}}{\text{Total Resistance}} \quad \dots (1).$$

¹ The resistance of the narrow region between the zinc A B appears to be *nil*; anyway, it is overcome by the chemical action and lies altogether beyond the range of our enquiries.

Again the P.D. of the extremities of the *external* circuit is the T.P.D.; hence by the same equation we have—

$$\text{Current} = \frac{\text{T.P.D.}}{\text{External Resistance}} \quad \dots (2).$$

Lastly, the P.D. of the extremities of the *internal* circuit is the internal drop; hence in the same way we have—

$$\text{Current} = \frac{\text{Internal Drop}}{\text{Internal Resistance}} \quad \dots (3).$$

which may also be conveniently written—

$$\text{Internal Drop} = \text{Current} \times \text{Internal Resistance} (4).$$

The two latter results are clearly particular cases of (3) and (4), § 136.

If E denote the E.M.F., V the T.P.D., C the current, B the internal resistance, and R the external, the above four equations may be written in algebraic forms, respectively as follows:—

$$C = \frac{E}{B + R} \quad \dots (1a).$$

$$C = \frac{V}{R} \quad \dots (2a).$$

$$C = \frac{E - V}{B} \quad \dots (3a).$$

$$E - V = BC \quad \dots (4a).$$

It is now easy to see why the T.P.D. of a given cell becomes less as the external resistance is diminished. For as the external resistance decreases so of course does the total, and since the E.M.F. remains unchanged, equation (1) tells us that the current increases; then, since the internal resistance remains unaltered, equation (4) tells us that the internal drop increases, or in other words the T.P.D. decreases. In the extreme case where the current is on short circuit the T.P.D. is practically *nil*.

All the results of this article are of great service in Electrodynamics.

EXAMPLE:—A battery, whose E.M.F. is 12 volts and resistance 6 ohms, has its terminals joined by a wire of resistance 9 ohms. Find the current, and also the P.D. of the terminals.

To find the current we apply equation (1a). We have $E = 12$, $B = 6$, $R = 9$; hence

$$C = \frac{12}{6 + 9} = \frac{4}{5} \text{ ampère.}$$

Next to find the T.P.D., we apply equation (2a). R denoting the resistance of the wire and V the required T.P.D., we have

$$C = \frac{V}{R} = \frac{V}{9}.$$

But we have just found $C = \frac{4}{9}$

$$\therefore \frac{4}{9} = \frac{V}{9}$$

whence $V = 4$ volts.

After having found the current, we may also find the T.P.D. from equation (4) thus :—

Internal drop = current \times internal resistance = $\frac{4}{9} \times 9 = 4$ volts,

and if we now subtract this drop from the E.M.F. we get the T.P.D., thus —

$$\text{T.P.D.} = 12 - 4 = 8 \text{ volts, as before.}$$

EXERCISES —

1. In the preceding question find the current and T.P.D. when the connecting wire has a resistance of (1) 18 ohms, (2) 2 ohms.

2. The E.M.F. of a cell is 2 volts and its resistance 1 ohm. Find the internal drop when the circuit is closed by a wire of resistance (1) 2 ohms, (2) $\frac{1}{2}$ ohm.

3. In any cell or battery show that if the external and internal resistances are equal, the internal drop is half the E.M.F.

4. The E.M.F. of a battery is 20 volts and its resistance 15 ohms. Its terminals are connected by a wire of resistance 25 ohms. Find (1) the current, (2) the T.P.D. (3) the potential drop along half the wire, (4) the potential at its middle point supposing the negative terminal of the battery earthed.

(5). Give an account of the distribution of potential in a cell (1) on open, (2) on closed circuit.

6. The poles of an insulated cell are connected by a wire. Will the strength of the current in the wire be altered if one of its poles be afterwards connected by another wire to the gas-pipe? Give reasons for your answer.

7. (1903.) The resistance of a battery is 1 ohm, and the current through a wire A B, whose resistance is 5 ohms and which joins the terminals of the battery, is 1 ampère. If A B is replaced by another wire C D, the current is $\frac{1}{2}$ of an ampère. What is the resistance of C D?

*8. A dynamo is employed to light an incandescent lamp which requires a P.D. of 100 volts at its terminals and a current of 2 ampères. The dynamo

is some distance away from the lamp to which it is connected by a pair of feeders whose joint resistance is 4 ohms. Find the P.D. which the dynamo terminals must have in order that the lamp may be properly lighted.

139. Electrodynamic Measurements. In electrostatics there are two things we are more particularly called upon to measure or compare—viz., *potentials* and *charges*; these measurements we effect by the methods of § 40 and § 55 respectively.

In electrodynamics there are two things we are more particularly called upon to measure—viz., *potential-differences* and *currents*. The measurement of *resistance* is in general dependent upon these two.

140. Measurement of Potential-differences: the Condensing-Electroscope. We have seen (§ 36) that when a conductor whose potential is not zero is connected to the rod or cap of an electroscope with its netting earthed the leaves diverge.

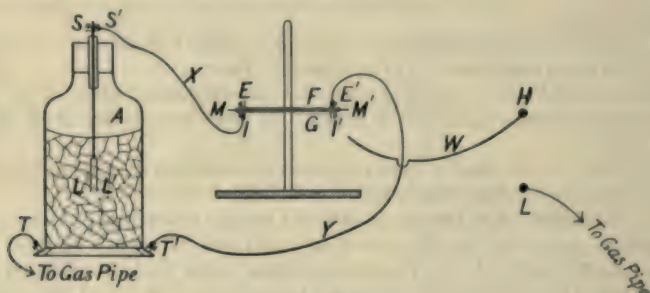


Fig. 91.

Hence it would appear an easy matter to indicate the T.P.D. of a cell. Thus, taking the cell an open circuit, if we earth its negative terminal, its positive terminal, and also any conductor thereto attached has, as pointed out in § 137, a potential equal to the E.M.F. of the cell; if therefore we connect the positive terminal with the rod of the electroscope, the leaves acquire a potential equal to the E.M.F. of the cell, and the potential of the netting being zero we shall expect divergence. But since the E.M.F. of a cell is at best about two volts, and the electroscope is not sufficiently delicate to respond to less than about fifty volts, this does not work in practice. We therefore need something further, and the requirement is met by the

Condensing Electroscope; this was first invented by Volta, but in its original form which is still retained in the majority of text-books, it is very difficult to make it work; the arrangement here described was devised by the present writer some years ago and has been found to yield excellent results without the least trouble.

The arrangement is shown in fig. 91. The electroscope A is the identical instrument depicted in fig. 8, p. 29, with its cap removed. F and G are two brass plates, which should be fairly thick, so that they be made and remain perfectly flat; the lower one is mounted on an ebonite stem and the upper is furnished with a handle whose material is of no consequence; each plate also has a pair of binding-screws, E E, I I'. The plate F is placed on G, *with a sheet of food-wrap paper, M M', between.* One of the binding-screws (E) of the upper plate is connected by a copper wire Y to the terminal T' of the electroscope, the other terminal T being connected to the gas pipe, so that the plate F and the netting of the electroscope are both well earthed. One of the binding-screws (I) of the lower plate G is connected by another copper wire X to the terminal (S) of the electroscope; in this way any potential which in any experiment may be conferred upon the plate G will if sufficiently strong cause the leaves to diverge (§ 36).

Now the two plates F and G clearly constitute a condenser (§ 72) of which the lower G is the insulated plate, the upper F the earth plate, and the paper the dielectric¹; also since the plates are very close together the capacity of the condenser is considerable.

The method of using the instrument is as follows:—Let H and L (fig. 91) be the high and low potential terminals respectively of a cell or battery.² Connect L to the gaspipe, and H to the terminal I' of the lower plate G by means of the wire W;³ then (§ 137) this plate acquires a + potential equal to the E.M.F. of the cell, *which is*

¹ The paper is of course but an indifferent insulator, but as the condenser is only going to be charged to a weak potential this does not matter.

² In practice, unless the electroscope be very delicate and great care be taken, experiments with a *single* cell are sometimes disappointing, but by employing three or four connected together so as to form a series battery (§ 151), excellent results may be ensured. For very accurate work with a single cell, Lord Kelvin's Quadrant Electrometer should be employed instead of the Condensing Electroscope.

³ The diagram shows the next stage of the experiment after the wire has been detached.

insufficient to affect the electroscope : so far, however, the manipulation is incomplete. Now, not only has the plate G acquired a + potential, but also (§ 137) a + electrostatic charge, and our next step is to *disconnect the wire W from the terminal I'*, so as to prevent this charge being subsequently lost. Finally comes the main feature of the experiment ; we *lift off the earth-plate F* so that G ceases to be part of a condenser at all, and becomes a mere isolated plate of vastly smaller capacity than when in presence of the earth-plate. But the charge on G still remains, and therefore *its potential is greatly increased* : accordingly *as soon as the earth-plate is lifted the leaves of the electroscope diverge*.

If we had dispensed with the earth-plate from the beginning, the plate G would still have acquired a potential equal to the E.M.F. of the cell, but on account of its much smaller capacity would have taken a much smaller charge ; the object of the arrangement is, in fact, to make the plate G draw a fairly big charge at the weak potential furnished by the cell, and then by lifting the earth-plate cause that charge to develop a much stronger potential.

If, after the earth-plate has been lifted, we hold over the electroscope a metal ball which has been beaten with india-rubber the leaves are found to diverge *more*, thus *proving* (cf. § 39) the charge on the plate G to have been + and therefore by Poisson's Principle the potential of H to have been also +.

If we reverse the experiment by connecting H to the gaspipe and L to the terminal I', we get the same effects, except that now the divergence is increased by holding over the electroscope a metal ball beaten *with fur*, thus showing the charge on G and the potential of L to be -.

Hitherto we have supposed the cell to be on open circuit. But it works in the same way on closed circuit, except that the divergence of the leaves is not so great ; also the divergence is less the less the resistance of the wire used to connect H and L : this affords direct experimental proof of what was said in § 138 respecting T.P.D. and E.M.F.

We may also employ the method to prove the statement in § 137—viz., that the E.M.F. depends simply upon the *kind* of cell, and not upon its size, etc. For this purpose we take several cells, all of the same kind, but differing in other respects. Taking first one of them, we connect its terminals (on open circuit) with the earth and con-

denser, as in fig. 91; and on lifting the earth-plate we obtain a certain divergence. We then do the same in succession with the others: *in each case it is found that the divergence is the same.* A gallon-size Daniell cell, for example, gives the same divergence as one holding only a quarter of a pint, and therefore has the same E.M.F.

It may be noted that in all experiments with the condensing electroscope it is very usual in practice to *omit the gas-pipe connections*, and merely run a wire direct from the netting or earth-plate to the terminal of the cell that otherwise would go to the gas-pipe; thus, in fig. 91, a wire would connect L to T' or E: the action is in all respects the same.

141. Measurement of Currents: the Tangent Galvanometer.

To measure currents we employ an instrument called a *galvanometer*. There are many forms of galvanometer, but they all depend upon the same principle—*viz.*, that when a current flows along a wire near

to or encircling a magnetic needle, it in general *deflects the needle*. This fact, which is of

very great importance in electro-dynamics, may be shown by the contrivance in fig. 92,

which is a simple form of the particular kind of galvanometer known as a *tangent galvanometer*.

A B A' B' is a horizontal graduated circle of brass or stiff cardboard; and on a pivot P,

at its centre, is balanced a compass needle. C D E D' C' is a vertical hoop of stout copper wire,

and the zeros of the graduated circle are in the plane of this hoop. The whole is fixed on wooden supports, as shown. The ends C, C', of the

hoop enter the supports, and are prolonged beneath the woodwork to binding-screws T, T', into which they are permanently soldered,

while the upper parts of T, T', stand above the wooden base in which they are firmly screwed. The instrument is set on the table, and turned until the needle *n s* points to the zero; we then know

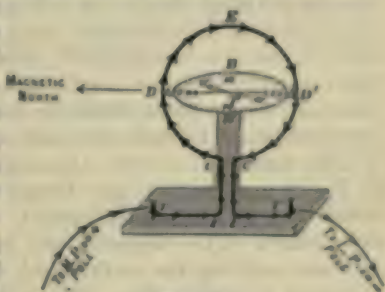


Fig. 92.

that the hoop C D E D' C' is in the magnetic meridian. Now con-

nect the terminals T, T', to the H.P. and L.P. poles of a voltaic cell. This closes the circuit; a current flows round the hoop in the direction of the arrows, the needle becomes deflected, and (after a few swings) comes to rest in a new position, $n' s'$. The angle $n P n'$ between its old and new position is called its *deflection*, and can be read off on the graduated circle. The needle is now under influences analogous to those in fig. 78, p. 143; as we shall see in Chap. IV., the current produces a magnetic field which tends to make the N. pole of the needle point (magnetic) east,¹ while the earth's field tends to make it point north, and it takes up a position in which the forces on it due to the two fields balance one another. Moreover, the stronger the current the greater will be the force due to its field, and the greater will be the deflection, so that the magnitude of the latter gives us an estimate of the strength of the former. If the current were enormously strong the deflection would be very nearly 90° , but it is never possible to make it *exactly* 90° .

The instrument in fig. 92 is called a *single-coil galvanometer*, because the hoop consists of one turn only. Such an instrument is not much good for very weak currents, say less than about $\frac{1}{4}$ ampère, and for these a *multiple-coil galvanometer* is employed. In the latter instrument we use *insulated* copper wire—that is, wire covered with silk, cotton, gutta-percha, or some insulating material—and the hoop consists of a number of turns wound close together in the form of a flat spiral. If n denote the number of turns, the current entering at T will pass up to C and thence travel n times round the hoop before emerging along the route C' F' T'. The effect is to multiply the strength of the magnetic field due to the current by n , without of course altering the earth's field, so that for a given current the deflection is greater than with a single coil, and the greater n is the greater is the deflection. In this way, by using a few dozen coils, currents down to about $\frac{1}{100}$ ampere can be readily recognised.

In the instrument shown in fig. 92 the needle is long; for elementary purposes, where we merely wish to see which of the two currents is the stronger, this does not matter, but when the galvanometer is required for the *accurate measurement* of a current the

¹ It will be east as the figure is drawn: if the current went the opposite way round the hoop it would be west. This will receive detailed study in Chapter V., but meanwhile it should be noted that with a given instrument reversing the current reverses the deflection of the needle.

needle must be very short. The best instruments are accordingly made in this way, and the needle has fixed to it a light aluminium pointer which runs over the scale, and by means of which the deflections are read.

Any simple galvanometer not intended for accurate measurements is sometimes called a *galvanoscope*.

The tangent galvanometer derives its name from the fact that, with a given instrument, the current is proportional to the "tangent" of the angle of deflection as defined in Trigonometry; provided, however, this angle be fairly small it is very nearly proportional to the angle itself—thus a current giving a deflection of 15° may be taken as three times as strong as one giving a deflection of 5° .

EXERCISES:—1. If a current of half an ampère deflects a certain tangent galvanometer 20° , what will be the strength of the current that deflects it 8° ?

2. (1902) The deflection of a galvanometer is 10° when connected directly to a small Daniell cell. When a long coil of fine wire is placed in the circuit, the deflection falls to 5° . Compare the resistance of the coil with that of the rest of the circuit, assuming that the deflection is proportional to the current.

142. High and Low Resistance Galvanometer. In the tangent galvanometer the needle turns horizontally, but for some purposes one in which it turns vertically

is to be preferred. A very convenient form of vertical galvanometer (or rather galvanoscope) is shown in fig. 93. E G F H is a horizontal wooden base wherein is a slot, C D, about $\frac{1}{4}$ inch wide, and in this swings a rather heavy magnetic needle, *n*, about a horizontal axis, K; the needle therefore turns in a vertical plane. Attached to the needle is an aluminium pointer, P, which runs over a

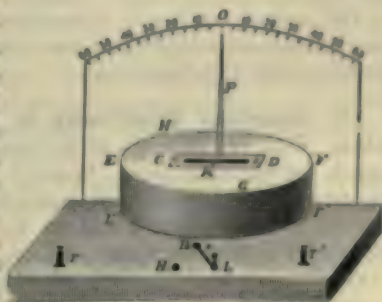


Fig. 93.

graduated scale. The axis K is a trifle above the centre of gravity of the needle so that the weight of the latter practically

counteracts the force of the earth's magnetism, and when no other magnetic influence is present it sets horizontally, with the pointer P at the zero of the scale. The base E G F H constitutes the top of a bobbin, E E' F F', round which are wound *two separate coils* of insulated copper wire; one of these is fairly stout, and of only a few turns, so that its resistance is low; the other is fine and of many turns—its resistance is therefore high: these wires are not seen in the figure. The instrument is furnished with a switch-handle, X, working on a button, B, and which can be turned so as to make contact with either of the buttons, H or L, as required, and the windings are so arranged that when the switch is on L, as in the figure, the low-resistance coil only is in circuit, while when on H the high-resistance coil only is in circuit; we have thus a high and low resistance galvanometer in one instrument, which for many purposes is a great advantage.

Suppose now, the switch being on either of the buttons H or L, the terminals T, T', are connected with the poles of a cell or battery: the current will flow round one of the coils and deflect the needle, thus causing the pointer to travel over the scale. The amount of deflection will in any case be such that the turning effect due to the weight of the needle in its displaced position just balances that due to the current. For *a given one of the coils*, say the low-resistance one, the stronger the current the greater is the deflection.¹

This instrument is very convenient, but no vertical galvanometer can be made so *delicate* as a horizontal one on account of the much greater friction on the pivot.

143. Important Experiment on E.M.F., Current, and Resistance. Take any two cells of the same kind, say two Daniell's, one small, and one very large. Connect the terminals of the small one to those of a multiple coil tangent galvanometer, and notice the deflection. Then detach and do the same with the big one. The deflection in the latter case will be greater, showing that we have a *greater current*. But by § 140 the E.M.F. of the two cells is the same. Hence, by Ohm's law (equation 1, § 138) the total resistance

¹ We cannot immediately judge of the relative strengths of two currents one of which passes through one coil and one through the other, nor indeed do we require to.

must be less when the big cell is used. But the external resistance—*viz.*, that of the galvanometer—is the same in both cases, because it is the same identical instrument. Hence, *the resistance of the big cell must be less than that of the small one.* Which proves experimentally what was argued out on theoretical grounds in § 135.

EXERCISE:—You are supplied with two wires, and are required to determine which of them has the greater resistance; how would you proceed?

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER I.

1. Chemical action of dilute sulphuric acid on metallic zinc (§ 137).

2. The simple voltaic cell (§ 133).

3. The current of a voltaic cell is of the same strength at all parts of the circuit, external and internal, but the potential is not. The top of the potential gradient is at a layer, A B (fig. 90, No. 1), very near the zinc plate and the bottom of the zinc plate itself; the electricity flows of its own accord down the gradient from A B across the liquid to the copper plate, and thence through the wire to the zinc, whence it is pumped up again to the top, A B, by the chemical action of the cell (§§ 134, 138).

4. The E.M.F., of a cell or battery is defined to be the P.D. of its terminals *on open circuit*; it depends simply upon the *kind* of cell. But the internal resistance depends in addition upon the *size*, etc., of the cell. The T.P.D. of a cell on *closed circuit* is *less* than its E.M.F. (§§ 137, 135, 138).

5. Ohm's Law (1) in the general form (§ 136), applicable to any dead circuit; (2) in the specialised forms (§ 138), applicable to cells and batteries. Potential Drop (§§ 136, 138). The *Volt*, *Ohm*, and *Ampère* (§ 136).

6. The resistance of a wire depends upon its material, length, and thickness. For wires of the same material the resistance is proportional *directly* to the length, and *inversely* to the sectional area. Copper is the best conductor for practical use, on account of its low specific resistance (§ 135).

7. The Condensing Electroscope and the explanation of its action. How to use it to prove (i) that the potential of the terminal commonly called positive really is higher than that of the one called negative; (ii) that the T.P.D. of a cell on a closed circuit is less than its E.M.F.; (iii) that the E.M.F. of a cell is independent of its size, etc. (§ 140).

8. Galvanometers and Galvanoscopes; their construction and principle of action (§§ 141, 142).

9. How to prove experimentally that the resistance of a cell depends on its size, etc. (§ 143).

CHAPTER II.

VOLTAIC CELLS AND BATTERIES.

144. Defect of the Simple Cell. Set up a simple cell, connect its poles with the terminals of a multiple coil tangent galvanometer, and note the deflection of the needle. Allow the whole concern to remain a few minutes : the deflection will gradually become less, and after perhaps five or ten minutes will be practically *nil*. This clearly shows a falling off of current strength. Now look at the copper-plate ; it will be found covered with minute bubbles of hydrogen. Take it out, clean it well, so as to remove the adhering hydrogen, and put it back : the cell will now give as good a current as at first, but again it will soon fall off, and so on.

The accumulation of hydrogen therefore renders the cell inefficient. But how does the hydrogen act ? It must do so either by increasing the resistance of the cell, or diminishing its E.M.F., or maybe both. Let us appeal to experiment :—Set up the condensing electroscope, take a freshly prepared simple cell and test its E.M.F. by the method of § 140, noting the divergence of the leaves. Then detach, put the cell on closed circuit for a few minutes, then remove the wire connecting the poles, and again test with the condensing electroscope. The leaves will now diverge very slightly or not at all. The cell has, therefore, *lost most of its E.M.F.* Doubtless its resistance has also increased at the same time owing to the presence of the hydrogen layer, but that is a small point—the loss of E.M.F. is the main thing. If we now take out the copper plate, clean it well, refit the cell, and again test by the electroscope, the E.M.F. will be found restored.

But *why* should the hydrogen layer destroy or diminish the E.M.F. of the cell ? To answer this completely would necessitate the prior

consideration why does a cell have any E.M.F. at all? Now, the whole theory of the action of a voltaic cell is very perplexing, and scientific authorities are by no means agreed thereon; we therefore purpose avoiding it as much as possible, but the following generally received view appears accurate so far as it goes:—Whenever there are immersed in a liquid two plates of different metals, one of which is capable of being acted on chemically by the liquid and the other is not, the plates acquire a P.D., so that the combination constitutes a voltaic cell, and *the plate that is acted on always constitutes the L.P. or negative pole*; also (§ 137) the value of this P.D. on open circuit constitutes the E.M.F. of the cell. Moreover the E.M.F. depends upon the degree of attackability¹ of the first plate, thus if in the simple cell we employ iron in the place of zinc we get a feeble E.M.F., because the iron is less attackable. Suppose now we employ two metals *both* of which can be attacked but in different degrees—*e.g.*, zinc and iron,—then the action of the liquid on the zinc tends to make the potential of the zinc the lower, while its action on the iron tends to make the potential of the iron the lower, and on the whole there is a small balance in favour of the zinc being the lower, so that the combination constitutes a cell of feeble E.M.F. in which the iron is the H.P. terminal. In fact the iron introduces a *back E.M.F.* which subtracts from that due to the zinc, the *actual* E.M.F. being the difference between the two.

Now in the ordinary simple cell, the hydrogen on the copper plate is in what is known in chemistry as the “nascent state”² in which condition it is fairly attackable by the acid, though in a less degree than the zinc: it therefore acts very much as an iron plate would do, introducing a back E.M.F. which becomes more marked the more the hydrogen is allowed to accumulate.

EXERCISE:—What is the E.M.F. of a cell in which both plates are of zinc?

145. Other Kinds of Cell. Smee's Cell. When the hydrogen accumulates on the copper, platinum, or other H.P. plate of a simple

¹ This term is confessedly vague.

² This term is applied to elements just in the act of being liberated from some combination.

cell, the plates are said to become *polarised*, and the back E.M.F. thus called into play, is called the *E.M.F. of polarisation*. Numerous forms of cell have been devised in which polarisation is more or less successfully overcome, either by removing the hydrogen from the H.P. plate or preventing its deposit thereon. The simplest and oldest of these is the *Smee Cell*. It is a simple cell in which the copper plate is replaced by one of "platinised silver"—that is, silver covered with finely divided platinum so as to give it a rough surface; the roughness to some extent prevents the hydrogen adhering to the plate, but the action is not very satisfactory.

It will be observed that in a Smee cell the hydrogen is first allowed to form on the plate, and is then removed by *mechanical* means. In the other cells which we shall now proceed to consider, the removal is effected by *chemical* means, some substance being used in the cell which attacks the hydrogen and really prevents its ever forming on the H.P. plate at all. The substance producing this effect is called the *depolariser*.

In some forms of cell, notably the Daniell, the E.M.F. remains practically unchanged, even though the circuit be kept closed for several hours: such are termed *constant* cells. In others, as the chemical action progresses, the E.M.F. falls with greater or less rapidity.

The student should be careful not to confuse between the *fall of E.M.F.* of a cell and the *internal potential drop* (§ 138); the latter is common to all cells and occurs immediately they begin to work. Looking at fig. 90, No. 2, the internal drop occurs between the layer A B and the copper or other corresponding plate, and is the result of the current having to overcome the resistance of the liquid; but the fall of E.M.F. occurs in the narrow region between A B and the zinc plate, and arises from some modification of the chemical action.

146. Grotthüs's Hypothesis. Now, there was a point respecting the simple cell left over in § 133 for future consideration—viz., *why does the hydrogen appear on the copper plate?* And we shall be the better able to understand the various other cells if we clear this up. We shall adopt the explanation originally given by Grotthüs, and known as the *theory of alternate combination and dissociation* :—

In fig. 94 consider the cell freshly fitted up and on open circuit. Between the zinc and copper plates there are many millions of molecules of sulphuric acid, each having the composition H_2SO_4 , or SO_3H_2 : let us for simplicity represent these by six only,

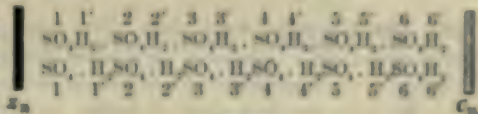
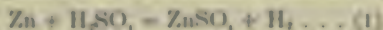


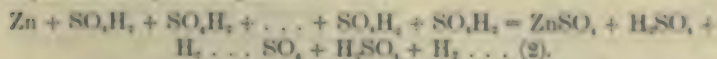
Fig. 94.

arranged as in the upper row. Here the sulphurion 1 is combined with the hydrogen 1', the sulphurion 2 with the hydrogen 2', and so on. We now close the circuit, and chemical action sets in between the zinc and sulphuric acid in accordance with the equation—



The lower row now represents what is conceived to occur. An atom of zinc combines with the sulphurion 1, forming the group ZnSO_4 , shown on the left, and liberating the hydrogen 1'. *But this hydrogen does not appear in the free state*; it combines with the sulphurion 2, forming a new molecule of sulphuric acid H_2SO_4 . This liberates the hydrogen 2', which combines with the sulphurion 3, forming H_2SO_4 , and so on, right throughout the whole string of molecules, until we come to the one adjacent to the copper. Here the hydrogen 6', liberated from its previous combination with the sulphurion 6, finding no more sulphurion to unite with, makes its appearance in the free state on the copper. Thus, in equation 1, the H_2 on the right-hand side is *not the identical H_2 belonging to the H_2SO_4 which attacks the zinc, but belongs to a different molecule altogether*. The hydrogen is conveniently said to “travel” from the zinc to the copper by alternate combination and dissociation, though in reality it does not travel at all.

The action according to the above view may be conveniently represented by the equation—



It may be mentioned in direct experimental support of Grotthüs's theory, that if while the cell is working, a copper or platinum plate not connected with either of the cell-plates be put anywhere between

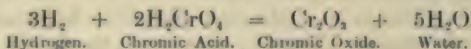
them, the side of it facing the zinc becomes covered with bubbles of hydrogen.

147. The Chromic Acid Cell. The usual form of this cell is shown in fig. 95. It consists of a glass bottle fitted with a wooden or ebonite cap; attached to the under surface of the cap is a strip of brass, to which are cemented two parallel plates of gas coke, and one of the terminals, *a*, is connected with the brass, so that it constitutes the H.P. pole of the cell. Through the centre of the cap is a brass tube *insulated from the plate beneath*, and in this slides a brass rod carrying at the bottom an amalgamated zinc plate: the terminal *b* is connected by a brass strip above the cap to the tube, and thus constitutes the L.P. pole of the cell. The liquid employed is a mixture of dilute sulphuric acid and chromic acid, the latter being the depolariser; and since this mixture attacks the zinc *even in open circuit*, the zinc plate is drawn up by means of the sliding rod when the cell is not in use.

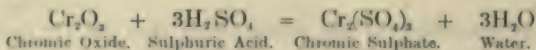


Fig. 95.

The main action of the cell is the same as in the simple cell. The depolarising action consists in the chromic acid attacking the hydrogen which would otherwise appear on the carbon plate according to the equation—



Thus no free hydrogen appears; it simply forms water along with the hydrogen belonging to the chromic acid. The chromic oxide dissolves in the excess of sulphuric acid present according to the equation—



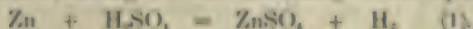
Chromic sulphate is green, while chromic acid is red. As the materials become used up the colour of the liquid changes from red to brown, and from brown to green, by which time it is useless.

The chromic acid cell is a modern improvement on the old bichromate or Poggendorf cell. In the latter, potassium bichromate was used in place of chromic acid, and chrome alum was formed as

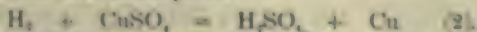
a waste product (instead of chromium sulphate), which crystallised on the plates and choked them up.

A freshly prepared chromic acid cell has an E.M.F. of about 2 volts. On closing the circuit and thus making the cell work, its E.M.F. retains this value for a short time, and then begins to run down. After using a few times, the chromic acid becomes partly exhausted, and in general the cell cannot be relied on for more than about 1.7 volt, and that is liable to fluctuation. Size for size, its internal resistance is low compared with a good many other cells; and as very little trouble is involved in its use, it is a great favourite in laboratories and lecture-rooms when a fairly strong current is needed for only a minute or so at a time.

148. Daniell's Cell. The form of this cell most commonly met with is shown in fig. 96. It consists of a cylindrical copper pot in which is a concentrated solution of copper sulphate. In this stands a *porous pot*—i.e., a pot of unglazed earthenware through which liquids can slowly diffuse. In the porous pot is dilute sulphuric acid, and in this a rod of amalgamated zinc supported by a wooden lid which rests on the pot. Binding-screws are attached to the zinc rod and copper pot, and constitute the L.P. and H.P. poles of the cell respectively. Between the two pots and near the top is a perforated ledge, on which rest crystals of copper sulphate; these are covered by the copper sulphate solution, and as the latter becomes weakened by the action of the cell they dissolve, thus keeping the solution concentrated. The main action consists (as in the simple cell) in the sulphuric acid attacking the zinc according to the equation—



The H_2 “travels” by alternate combination and dissociation (§ 146) as far as the porous pot, where it encounters copper sulphate. The following action here takes place:—



Hydrogen. Copper-sulphate. Sulphuric Acid. Copper.

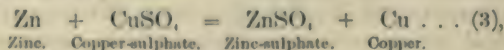
The copper thus liberated now “travels” in like manner through the CuSO_4 solution until it meets the copper pot, on which it deposits itself. The result is that after the cell has worked some



Fig. 96.

time the inner surface of the copper pot becomes coated with a dull red layer of finely divided but firmly adherent copper. *But no free hydrogen makes its appearance anywhere.* The depolariser is manifestly the copper sulphate, and the depolarising action is the action (2) which occurs at the porous pot, and consists in the substitution of copper for hydrogen.

Taking equations (1) and (2) together, it will be seen that the *total* action in a Daniell cell consists in the replacement of Zn by Cu according to the equation—



the H_2SO_4 playing on the whole no part whatever. The practical upshot of this is that we may do away with the latter, and in its place employ a solution of zinc-sulphate in the porous pot; this is frequently done, and has the advantage that there is no danger of the zinc being eaten away when the cell is not in use. As previously pointed out (§§ 136, 137) the E.M.F. of a Daniell cell is about 1·1 volt, and remains remarkably constant, even though the cell be kept in use a long time; this is especially true of the zinc sulphate form. Taken size for size its resistance is high compared with that of most other cells; a pint size has a resistance of about 3 ohms, while that of a pint chromic-acid cell is only about $\frac{1}{4}$ ohm. But, like its E.M.F., it remains practically constant while working, so that it is the best cell we have for producing steady currents of no great strength. A specially constructed form is largely used in connexion with the Post Office Telegraphs.

The Daniell cell is an example of “two-fluid” cells—that is, cells wherein two liquids are employed, separated by a porous partition. The simple and chromic-acid cells, on the other hand, are “one-fluid” cells.

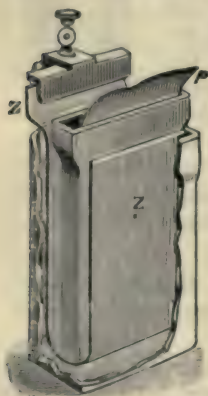
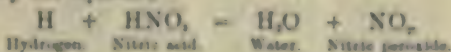


Fig. 97.

149. Grove's Cell. This is shown in fig. 97. It consists of a stoneware jar containing dilute sulphuric acid, wherein is placed a bent plate of amalgamated zinc, Z Z. In the bend rests a porous pot containing strong nitric acid, and in this is a platinum

plate, P. The latter is supported by a strip of wood¹ (not shown), and is fixed against it by a binding-clamp, which constitutes the H.P. pole. The L.P. pole is a similar clamp attached to the zinc. The main action is the same as in the preceding cells. The hydrogen "travels," as in § 146, as far as the porous pot, and here it meets the nitric acid, which is the depolariser. The depolarising action is represented by the equation—



The hydrogen is thus replaced by nitric peroxide. Now the latter is a gas, very soluble in strong nitric acid, and it accordingly dissolves therein, and does not appear on the platinum plate.

The E.M.F. of a freshly fitted Grove cell is about 1·9 volt, and remains fairly constant for some time after closing the circuit. Its internal resistance is extremely low, that of the pint size being about $\frac{1}{2}$ ohm. The cell is, in fact, the best known for strong and fairly steady currents.

150. The Leclanché and Agglomerate Cells. These differ from all the preceding cells in the fact that the exciting liquid is not sulphuric acid, but a concentrated solution of ammonium chloride, so that the *main* action is different. The Leclanché is shown in fig. 98. It consists of a glass bottle containing the ammonium chloride solution, and in this is a zinc rod (which need not be amalgamated) furnished with a copper wire and binding-screw (the latter not shown), which constitutes the L.P. pole. The other plate is of gas coke, and the terminal thereto attached is the H.P. pole. The depolariser is not a liquid, but a packing of black oxide of manganese and bits of carbon, the latter being added to prevent too great compactness. The packing is contained in a cylindrical porous pot (preferably with a few small holes in its side), and the gas-coke plate is permanently embedded in it.

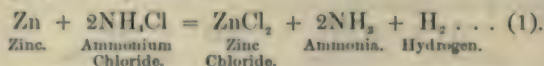
The agglomerate cell differs from the Leclanché in the absence of the porous pot; the depolarising mixture is made into compressed



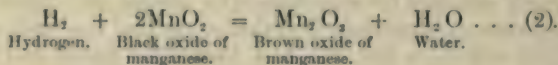
Fig. 98.

¹ Or, when a battery is used, by the zinc of the adjacent cell.

cakes, and the gas-coke plate is placed between two of these, which are pressed against it by india-rubber bands. This form of cell is superior to the Leclanché in having less resistance; in other respects it is electrically and chemically the same. The main action in either of the cells consists in the ammonium chloride attacking the zinc according to the equation –



The zinc chloride dissolves in the excess of ammonium chloride, forming a double salt; the ammonia dissolves in the water, while the hydrogen “travels” in the approved Grotthüasian manner as far as the depolariser, when the following action sets in:—



The actual E.M.F. of a freshly prepared Leclanché or agglomerate is about 1·4 volt, and the internal resistance (especially of an agglomerate) is considerably less than that of a Daniell of the same size. On closing the circuit the E.M.F. rapidly falls, the reason being that the depolarising action (2) is feeble, and after a few seconds more hydrogen is liberated than the black oxide of manganese can effectually dispose of, thus permitting partial polarisation. On again opening circuit and allowing a little time, the action (2) goes on until the excess of hydrogen is all oxidised off and the cell is ready for a fresh start. These cells are therefore quite useless for long-continued currents, but are admirably adapted for intermittent ones of short duration. They have the great practical advantage that, when once fitted up and used for intermittent work only they will last for many months without attention. They are of great service for electric bells and telephone calls.

151. Batteries. The term *battery* is commonly applied to any combination of two or more cells. There are three classes of batteries—viz., *series*, *arc* (or *parallel*), and *compound circuit* batteries, which differ in the mode of arrangement of the cells. The two latter are comparatively seldom employed, and we shall deal only with the first class; indeed, when a “battery” is spoken of it is in general understood to be a series battery.

The word "series" is employed generally to denote the arrangement of a number of things in such a way that *the same current passes through one after the other without branching*: for example, if we connect the poles of a cell with the terminals of a galvanometer, the cell and galvanometer are said to be in series.

Figs. 99 and 100 show a series battery on open and closed circuits respectively. The cells are depicted as simple cells, but it must be



Fig. 99.

distinctly understood that the diagrams are *typical*: the cells may be of any kind whatever, and all our observations perfectly general. In practice it is usual to have all the cells alike, and we shall suppose this the case. In the diagrams four cells (1, 2, 3, 4) are represented, but there may be any number. The connexions are as shown. The

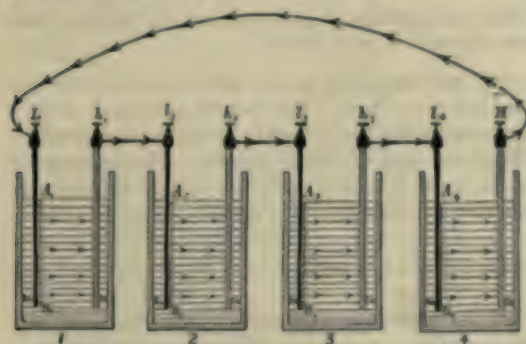


Fig. 100.

H.P. pole A_1 of No. 1 is connected by a short thick wire or any convenient clamp to the L.P. pole L_1 of No. 2, the H.P. of No. 2 to the L.P. of No. 3, and so on. This leaves the end poles, L and H, of the first and last cells free, and these constitute

the terminals of the battery, to which as in fig. 100 the external circuit is joined.

Now, to understand the advantage of the series arrangement let us study fig. 99. Let ϵ denote the E.M.F. of each separate cell. Then

the potential of h_1 exceeds that of L by e . Since no current is flowing the potentials of h_1 and L_2 are equal by Poisson's Principle. In the same way the potential of h_2 exceeds that of L_2 by e , while the potentials of L_2 and h_2 are equal; and so on. Hence, as we travel in imagination from L to H , the potential makes four jumps up, each equal to e , so that the potential of H is $4e$ above that of L . In other words the E.M.F. of the battery is $4e$. And in general if there be n cells, each of E.M.F. e , the E.M.F. of the battery is ne . This is a most important point, and is the one to which the practical value of a series battery is due. *We get increased electromotive force.* For example, with a single Grove, we can at best get only 1.9 volt, but with twelve such series we get 1.9×12 , i.e. 22.8 volts.

EXERCISES:—1. What is approximately the E.M.F. of a series battery of 20 Leclanché cells?

2. Show that if a number of cells of different kinds be connected in series, the E.M.F. of the resulting battery is the sum of those of the separate cells.

3. Four cells, each of E.M.F., e are joined in series, and by accident one of them is put in the wrong way, that is its H.P. terminal is connected to the H.P. terminal of its neighbour. What is the E.M.F. of the whole battery?

4. Draw a sketch of a series battery of three agglomerate cells on closed circuit, and also of four Daniells on open circuit.

In practice it is very convenient to have a battery of six, or eight agglomerate cells packed in a box. The box is provided with a couple of terminals, constituting the poles of the battery, and with a number of brass "buttons" and a switch handle. The buttons are connected to the cells in such a way that by merely moving the handle we can switch on any number of the cells in series, from none up to the full number in the box. Other cells may of course be fitted in the same way. We shall speak of such an arrangement as a "box battery."

The increase of E.M.F. obtained by connecting cells in series may be well shown by means of the condensing electroscope as follows:—Take a box battery, switch on one cell, and connect the terminals to the condenser as explained in § 140: on lifting the earth, plate very slight if any divergence will be observed. Now switch on two cells, and repeat the operations; the divergence will be fairly distinct. Repeat again with three cells, the divergence will be still greater,

and so on, until with five or six cells the divergence will be as great as if the cap of the electroscope had been beaten with fur, and a small spark may be obtained from it.

EXERCISE —5. A six-cell battery is taken on open circuit, the condensing electroscope experiment performed with it, and the divergence noted. The circuit is then closed by a wire of moderate resistance, and the experiment repeated. What difference, if any, will there be in the behaviour of the leaves? Explain your answer.

Let us now consider our battery on closed circuit (fig. 100). The current flows along the external circuit, from H to L, and back again through the cells and connexions as indicated by the arrows. In so doing it encounters the external resistance, and also the resistance of all the cells in succession. If b denote the resistance of each cell, and n the number of them, the resistance of all of them is clearly nb and adding to this the resistance R of the external circuit we obtain—

$$\text{Total resistance} = nb + R.$$

Now we have already seen that if e denote the E.M.F. of each cell,

$$\text{Total E.M.F.} = ne.$$

Hence if C denote the current we have by Ohm's law (equation 1, § 138)

$$C = \frac{ne}{nb + R} \quad (1).$$

EXERCISES —6. Twelve cells are connected in series. The E.M.F. and resistance of each are 1.5 volt, and two ohms respectively, and the circuit is completed by a wire whose resistance is $1\frac{1}{2}$ ohm. Find the strength of the current, and compare it with that given by only one of the cells with the same external resistance.

7. Work the foregoing question, substituting an external resistance of 100 ohms for $1\frac{1}{2}$ ohm.

After working these questions, the student will be struck with the fact that in No. 6, where the external resistance is small, the current given by twelve cells is practically no stronger than that from a single cell, while in No. 7, where the external resistance is big, it is very much stronger. Now, this is not a mere accident of the particular figures given, but a general principle; it can readily be deduced algebraically from 1, and the student should prove it in this way as

an exercise. Practically, however, it is more instructive to view the matter thus: Comparing a single cell with the battery, when we connect n cells in series we multiply the internal resistance by n . If now the external resistance be very small, *it makes very little difference anyway*, so that we have very nearly *multiplied the total resistance by n* . But we have also multiplied the E.M.F. by n . Hence the ratio of the two is very nearly the same, and therefore by Ohm's law the current is very nearly the same. But if the external resistance be big, it is the chief thing; the internal counts for a mere trifle, and whether it be multiplied by n or not is of small import. Hence putting the cells in series *leaves the total resistance pretty much the same as if there were but one cell*. But it still multiplies the E.M.F. by n . Hence the ratio of the latter to the former is nearly n times as great, that is by Ohm's law the current is nearly n times as great.

The general conclusion, therefore, is that with small external resistance it is of no practical advantage to use a series battery, but with big external resistance it is a great advantage.

The truth of this conclusion may be shown experimentally thus:—

Take a box battery, and connect its poles to the terminals of the high and low resistance galvanometer, fig. 93. Set the galvanometer-switch on the button L, so as to throw the *low-resistance* coil into circuit. Then switch on one cell, and notice the pointer-reading. Afterwards switch on, in succession, two, three, four, etc., cells: *the reading will be pretty much the same in each case*. Now switch off all the cells, set the galvanometer-switch on the button H, so as to put the *high-resistance* coil into circuit and repeat. *For every additional cell used there will be a decided increase in the pointer-reading*.

EXERCISES:—8. Find the strength of the current when a battery of E.M.F. 24 volts and resistance 36 ohms, has its poles connected by thick wires to the terminals of a galvanometer of resistance 12 ohms. Find also the potential difference of the galvanometer terminals.

9. Three cells all alike are connected in series, but one of them is put in the wrong way. The battery is then short-circuited. Compare the strength of the current with that given by one of the cells only (supposed also on short circuit).

10. You have given two batteries, A and B. You place A in circuit with a galvanometer, and get a certain deflection. You then substitute B for A.

and get a much smaller deflection. How would you find out whether this was because B's E.M.F. was less than A's, or because its resistance was greater?

The attention of the student is called to fig. 101 which is a conventional way of drawing any kind of series battery when the details of construction are not required to be shown. Each short thick line l , together with the adjacent long thin one, represents a single cell; l is the L.P., and h the H.P. plate, and the exciting liquid is imagined between them. The short horizontal lines represent the connexion between the successive cells. H and L are the battery terminals. The figure shows nine cells on closed circuit, the direction of the current being indicated by the arrows. Diagrams of this kind are easily drawn and are very useful.

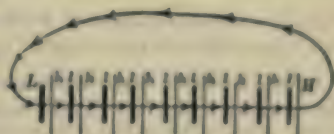


FIG. 101.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER II.

1. A simple cell is very inefficient: there is an accumulation of hydrogen on the copper (or platinum, etc.) plate, which produces a *back* E.M.F., thus causing the effective or actual E.M.F. to fall off. This phenomenon is called *polarisation* (§§ 144, 145).

2. Attend carefully to Grothius's theory (§ 146).

3. Attend carefully to the depolarising action of the several cells described in the text, and to the main chemical action in the Leclanché. Also to the zinc-sulphate form of Daniell.

4. The object of a *series battery* is to obtain *increased* E.M.F. If e denote the E.M.F. of each cell, that of n cells in series is ne (§ 151). A series battery is a great advantage when working with *high external resistances*.

EXERCISES ON CHAPTERS I. and II.

1. Draw a diagram of six simple cells in series. What happens if the terminals of the arrangement be connected by a wire and left so for a while? How would you prove experimentally the truth of your statement?

2. A strip of platinum and a strip of zinc dip into a vessel of acidulated water. How would you show that the two copper wires, fastened one to the zinc and the other to the platinum, are in different electrical states?

3. How would the action of a Daniell cell be modified if the solution of copper sulphate in the porous vessel were replaced by dilute sulphuric acid?

4. How would the action of a Daniell cell be modified if the copper pot and copper sulphate were replaced by a zinc pot and zinc sulphate?

5. With a battery made up of many cells, how would you show that the electrical conditions of the terminals differ from each other, and that the extent of the difference is greater, the greater the number of cells?

6. You have two box batteries, each of six Leclanché cells. In one the cells are small, in the other large. You try them each on open circuit with the condensing electroscope. Will there be any difference in the behaviour of the electroscope? If so, what? You next try them with a low-resistance galvanometer. What difference, if any, will there be in the pointer-reading? You lastly try them with a high-resistance galvanometer. Again, what difference, if any, will there be? Give reasons for all your answers.

7. Ten voltaic cells, each of E.M.F. 1.75 volt and resistance .75 ohm, are joined up in series, and the circuit completed by a wire of resistance 12.5 ohms. Find (1) the strength of the current, (2) the T.P.D. of the battery.

8. The poles of a voltaic cell are connected by a long wire. The wire is then cut and a galvanometer introduced into the circuit. Will it make any difference in the deflection of the needle according as the cut is made near the H.P. pole, near the L.P. pole, or at about the middle of the wire? Give reasons for your answer.

9. A simple cell is put in circuit with a multiple-coil tangent galvanometer, whose needle is observed to be deflected with its north pole eastward. It is left till the needle comes nearly back to the magnetic meridian. The zinc plate is then removed (care being taken not to disturb the copper), and replaced by one of platinum, and the circuit again completed. How will the needle behave? Give reasons.

10. In § 134 it has been pointed out that the current is the same at all parts of a circuit. But it was here tacitly assumed that the circuit *did not* branch. Now supposing it *does* branch, *e.g.*—suppose the poles of a battery are connected by two wires, what will then be the state of affairs?

11. How is polarisation prevented in a Daniell cell? How does a large Daniell cell differ from a small one in respect of (1) electro-motive force, (2) resistance?

12. Describe an agglomerate cell. Why does its E.M.F. diminish when it is short circuited?

13. Describe the zinc sulphate form of Daniell cell, and explain the chemistry of its action.

14. Two galvanic cells consist respectively of (1) plates of zinc and copper, (2) plates of zinc and platinum, dipped in dilute sulphuric acid of the same strength in each case. If the two zinc plates are joined by a wire, describe what occurs when the platinum plates are also joined by a wire.

15. (1899.) Two batteries A and B are made up of cells of the same kind arranged in series, A being composed of sixty and B of thirty cells. If the plates of a condensing electroscope are touched successively by the terminals of the two batteries and then separated, will the divergence of the leaves depend upon whether the order in which the two pairs of contacts are made is A B or B A? Give reasons for your answer.

16. Describe how you could make the leaves of an electroscope diverge from voltaic sources without the use of a condenser.

CHAPTER III.

ENERGY AND HEATING EFFECTS OF THE CURRENT.

*152. Preliminary Consideration; the Coulomb and Ampère-hour.

In § 134 we have seen that the electric current is analogous to the flow of water in a pipe. Now, the water current in a pipe is estimated by the amount of water that passes any cross section of the pipe in a given time, say the number of pints per second. In like manner we may conceive of the electric current as estimated by the amount of electricity that passes any cross section of the circuit per second. The amount that so passes where the current is one ampère constitutes the practical unit of quantity, and is called a *coulomb*; an ampère is thus a *coulomb per second*, or, in other words, a coulomb is an *ampère-second*. Practical electricians frequently employ the *ampère-hour* as the unit of quantity—it is obviously equal to 3,600 coulombs.

EXERCISE:—A house is fitted with an electric light installation taking 10 ampères, and kept going on an average two hours a day all the year round. Find how many ampère-hours and also how many coulombs are taken per annum.

*153. Work in any portion of an Electric Circuit. Consider any dead portion of any electric circuit, *e.g.*, A B, fig. 89, suppose a current of C ampères flowing in it, and let V volts be the P. D. of its extremities A and B. Then in one second C coulombs enter this portion of the circuit at A and leave it at B, so that they fall through V volts.

Now (§ 61), when a pound weight is lifted or falls through a foot the amount of work done is, as a matter of definition, called a foot-pound, whence it is inferred that when w pounds fall through h feet the work done is wh foot-pounds.

The fall of electricity through a P. D. is analogous to the fall of water or other material substance from a height, and in both cases work is done. Now, as a matter of definition, the work done by a coulomb in falling

through a volt is called a *joule*, and just as the work done by w pounds in falling through h feet is wh foot-pounds, so the work done by C coulombs in falling through V volts is VC joules. Hence in one second the work done by the electric current on the portion AB of the circuit is VC joules, or, in other words, the *rate of work* is VC joules per second.¹

Now the rate at which work is done is termed *power*, and the particular rate of one joule per second is termed a *watt*; a watt is thus a unit of power. We may now state our result, thus:—

When a current of C amperes flows through a portion of a circuit the P. D. of whose extremities is V volts, it delivers energy to that portion at the rate of VC watts. For shortness this may be written:—

$$\text{Rate of work} = VC \text{ watts} \quad . \quad . \quad . \quad (1)$$

or still more simply:—

$$\text{Watts} = \text{volts} \times \text{ampères} \quad . \quad . \quad . \quad (2)$$

the latter being the form usually quoted by electrical engineers, to whom the relation is of frequent service.

In the higher parts of the subject it is proved that a joule is equal to 7375 of a foot-pound, or a foot-pound to 1.356 joules. Now, what is known to engineers as a *horse-power* (H.-P.) is defined to be 550 foot-pounds of work per second (or 33,000 per minute); hence 1 horse-power = $550 \times 1.356 = 746$ watts. We may therefore throw equation (2) into the form.

$$\text{Horse-power} = \frac{\text{volts} \times \text{ampères}}{746} \quad . \quad . \quad . \quad (3).$$

EXAMPLE.—An overhead trolley wire is at a potential of 500 volts, and a car is taking 12 ampères, find the h.-p. supplied to the car. Also if the motor utilises 85 per cent. of the energy supplied, find the h.-p. at which it is actually running.

The current leaves the car by the rails at potential zero, and therefore the fall of potential is 500 volts. Hence by (3):—

$$\text{H.-P. supplied} = \frac{500 \times 12}{746} = 8 \text{ about.}$$

The h.-p. at which the car is running will be 85 per cent. of this, which is 6.8.

¹ If the portion AB be alive the same result is true, the only difference is that, if dead, the heat generated in AB is the exact equivalent of this work, which otherwise it is not; e.g., if AB contains an electric motor geared to a tram-car, part of the VC joules go to drive the car and only part to heat the coils of the motor.

EXERCISES:—1. Find the h.-p. required to run an electric light installation taking 90 ampères at 50 volts.

2. A *watt-hour* is defined to be the amount of energy supplied in one hour by a circuit delivering at the rate of one watt, and a Board of Trade Unit (B.O.T.U.) is 1,000 watt hours. Find, then, the cost of running the installation in the preceding question for 100 hours at 4d. per B.O.T.U. [The student should note that what we have to pay for is not electricity, but *electricity and voltage combined*, that is *energy*.]

3. A dynamo gives a T.P.D. of 550 volts and delivers to the external circuit a current of 186.5 ampères for 12 hours. Find (1) the h.-p., (2) the number of B.O.T.U. supplied.

4. A *Kilowatt* is defined as 1,000 watts. Find the T.P.D. of the terminals of a dynamo which is delivering to the external circuit 600 ampères and 300 kilowatts. Also find how many h.-p. go to a k.w.

5. An electric tram-car takes 15 ampères at 500 volts and runs at the rate of $7\frac{1}{2}$ miles an hour. It carries 80 passengers a two-mile journey at a charge of $1\frac{1}{2}$ d. per head, and the cost for the energy supplied is 1d. per B.O.T.U. Find the profit made on the journey exclusive of wages, wear and tear, etc. Also find the cost per "horse-power hour."

154. Heat developed in a Wire: Joule's Law. When a current passes through a wire, experiment shows that it becomes more or less heated; this is the principle of the electric incandescent or glow lamp, the "wire" in this case being a specially prepared carbon filament.

The wire being merely a dead part of the circuit the heat developed in it in any time is (§ 153) the exact equivalent of the energy delivered to it, and therefore by the preceding article is $V C$ joules per second, V being the P.D. of the extremities of the wire. It is however more usual to express the heat in times of the *resistance* and current. Now, if R be the resistance of the wire in ohms, we have by ohm's Law (equation 1, § 136), $C = \frac{V}{R}$, whence $V = R C$ and therefore $V C = R C^2$. Our result therefore is:—

Heat generated per second in a wire
 of resistance R ohms by a current
 of C ampères. $\left. \vphantom{\begin{array}{l} \text{Heat generated per second in a wire} \\ \text{of resistance } R \text{ ohms by a current} \\ \text{of } C \text{ ampères.} \end{array}} \right\} = R C^2 \text{ joules} \dots (1).$

This is known as *Joule's Law*; from it, it is clear that *for the same current the heat developed in a given time is proportional to the*

resistance, while for the same resistance it is proportional to the square of the current.

It should be carefully noted that the heating effect in a circuit is in no way dependent upon *which way* the current goes, whether from A to B or B to A; in this respect it strongly contrasts with the chemical and magnetic effects to be considered in subsequent chapters.

EXERCISES:—1. The resistance of the filament of an incandescent lamp is 80 ohms, and it carries a current of $\frac{1}{2}$ ampère. Find how many joules of heat are generated in it per hour.

2. A platinum wire of resistance 10 ohms is immersed in a pint and a half of water at the freezing-point. Find what current must be passed through the wire in order that the water may begin to boil after six minutes. [NB.—To raise a pint of water from freezing to boiling-point requires (about) 240,000 joules of heat.]

155. Rise of Temperature of a Wire. In the preceding article we have seen that if the same current be passed through two wires the rate of production of heat in them is proportional to their resistance. But a little consideration will show that the temperature they attain cannot follow the same law.

For example, suppose a current to pass through a uniform wire a foot long; the last eleven inches of it have eleven times the resistance of the first inch, and yet of course the wire attains the same temperature

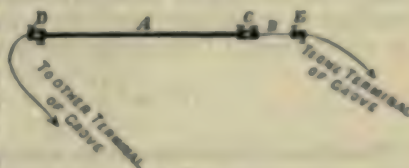


Fig. 102.

throughout. Again, consider the arrangement in fig. 102. Take two platinum wires A and B of equal resistances, A being long and thick, and B short and thin. Fix them together end to end by a binding-screw C, and join the ends D and E by other binding-screws and copper wires to the poles of a Grove battery of three or four cells. Then in both wires A and B the current is the same, and their resistance is the same, and therefore the rate at which heat is generated in them is the same. *But the wire B becomes white hot, while A remains merely warm.*

Now, why is this? When we first set the current through any wire it produces heat, which raises the temperature of the wire. But

at the same time heat escapes from the sides into the surrounding air by radiation, and as the temperature rises, this escape becomes more rapid. After a short time the heat escapes by radiation *as rapidly as it is produced by the current*, and *the temperature then rises no more* however long the current may be kept going; the wire has thus attained its final temperature, which remains unchanged so long as the current continues steady.¹

Referring now to fig. 102, when each wire has attained its final temperature,² since the rate of escape of heat from each is equal to its rate of production, and the latter is the same for both, *the rate of escape must be the same for both*. Now, it is explained in books on heat that in order that the rate of escape from two things may be the same, the one of greater surface must have the lower temperature. But the wire A has a much greater surface than B, and for this reason the temperature it attains is much lower.

It is not therefore fair to compare the *temperatures* of two wires with the same current simply by their resistances, or the temperatures in any case by the values of $R C^2$. The true law which is proved in the higher branches of the subject may be stated (approximately) thus:—Let a current of strength C flow through a wire, the specific resistance of whose material (§ 135) is r , and let d be the diameter of the wire. Then, if T denote the rise of temperature,

$$T \propto \frac{r C^2}{d^3} \quad (1).$$

From this it follows that *for the same current the rise of temperature is proportional directly to the specific resistance and inversely to the cube of the diameter*. Hence for the same current, thin wires get much hotter than thick ones of the same material, while those of the same thickness get hotter the greater their specific resistance.

This may be easily shown by experiment. Three wires—one of fairly thin copper, one of platinum of the same thickness, and one of much thicker platinum—are joined end to end, and a current from a

¹ Prior to the attainment of the final temperature, the temperature of the wire depends upon how long the current has been on; this, however, is a different question, and we do not here discuss it.

² It is not implied that they do this in the same time; as a matter of fact thin wires reach their final temperature almost instantly, while thick ones require longer; this, however, does not concern us.

Grove sent through them; the thin platinum wire then becomes much hotter than the thick one and also than the copper. It should be noted that it is not fair to make three *separate* experiments with the wires, using them one after the other to join the battery terminals, because the total resistance is then different in the three cases, and therefore by Ohm's law the currents are different: by connecting the wires end to end, as described, we ensure that *the same current goes* through all of them.

If we take a wire of the same material throughout, but thicker at some parts than others, and use it to join the poles of a battery, the current is the same throughout as also is the specific resistance. But the diameter is least at the thin parts, and hence by the above law *the thin parts become hottest*.

156. Effect of Rise of Temperature on the Resistance of Wires.

Take a Grove cell B (fig. 103), and by means of copper wires, A, A, A, arrange it in series with a spiral, W, of rather fine platinum wire, and a low-resistance galvanometer, G. Note the deflection of the needle. Then heat W strongly by a Bunsen burner: the deflection will become slightly less. Remove the burner and allow the wire to cool; the deflection will go up to its original value. This proves that the resistance of the wire W is slightly increased by a rise of temperature. The same is in general true of whatever material the wire be made *except carbon*, whose resistance is *decreased* under the same circumstances; the resistance of the filament of a glow lamp when well "alight" is about three-quarters that of the same filament when cold.

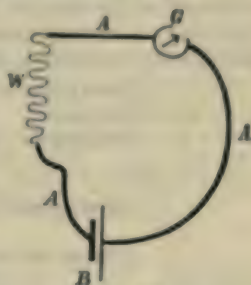


Fig. 103.

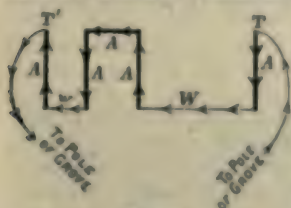


Fig. 104.

Fig. 104 shows another arrangement for illustrating the same thing. A, A . . . are stout copper wires (mounted on a frame and furnished with binding-screws, etc.), and W, w, are platinum wires stretched across. The terminals T, T', are connected with the poles of a Grove battery of two or

three cells, giving only sufficient current to make the platinum wires glow dull red. The wire *W* is then immersed in a pan of cold water, when the other one *w* becomes bright red or even white hot. The explanation is that the water cools *W*, thus diminishing its resistance; by Ohm's law the current then increases, and therefore since (§ 153), other things being the same, the rise of temperature is proportional to the square of the current, the temperature of *w* rises.

157. Work in a Battery Circuit. Efficiency. The relations of § 153 may be applied to the several parts of a battery circuit considered in § 138.

The rate of work in the *complete* circuit is the same as the total power developed by the chemical action of the battery; hence bearing in mind that the P. D. of the extremities of the complete circuit is *E*, the E.M.F. of the battery, we have by equation (1) § 153.

$$\left. \begin{array}{l} \text{Total power} = EC \text{ watts} \dots\dots\dots \\ \text{or, as it is often written,} \\ \text{Total watts} = \text{E.M.F.} \times \text{current} \dots\dots\dots \end{array} \right\} (1).$$

In like manner we have

$$\text{External watts} = \text{T.P.D} \times \text{current} \dots\dots (2),$$

and

$$\text{Internal watts} = \text{internal drop} \times \text{current} \dots (3).$$

Of the last two items, (2) is the power available for external use, while (3) is the power wasted in heating the battery. Now, in any machine or other contrivance for the supply of energy, the ratio

$$\frac{\text{Power available}}{\text{Total power supplied}}$$

is called the *efficiency* of the machine; hence, from (1) and (2), we learn that

$$\text{Efficiency of a battery} = \frac{\text{T.P.D.}}{\text{E.M.F.}} \dots\dots\dots (4).$$

A rather important consequence follows from (1), viz., that if we increase the current supplied by a battery (by diminishing the external resistance) we increase its output of power, and therefore the rate of consumption of its material; in other words, increasing the current makes the battery *work harder*. Practical electricians usually estimate the "life" of a cell or battery as so many ampère-hours (§ 152); clearly the harder it is worked the shorter will be the time before it is exhausted.

EXERCISES.—1. Show that the efficiency of a battery is less the greater the current taken from it. [NOTE.—The student should take care not to confuse between the *efficiency* and the *actual external power*; as the current increases from zero the latter increases up to a certain point and then decreases, and it is proved in the higher parts of the subjects that the external power is greatest when matters are so arranged that the T.P.D. of the battery is half its E.M.F., or which is the same thing when the external and internal resistances are equal, or when the current is half what it would be on short circuit.]

2. Six cells, each of E.M.F. 1.5 volts and resistance 2 ohms, are connected in series, and the terminals of the battery thus formed joined by a wire of resistance 15 ohms. Find how many watts are developed in the external circuit, and the efficiency of the installation; also find the horse-power at which the battery works.

3. Find the internal resistance of a dynamo in order that when working against an external resistance of $4\frac{1}{2}$ ohms, it may have an efficiency of 90 per cent. [N.B.—The dynamo may be supposed to follow the same laws as a battery.]

4. An electric pocket-lamp has a resistance of 20 ohms, and is animated by a small dry battery of resistance 10 ohms and E.M.F. 6 volts. The life of the battery is estimated to be $\frac{1}{2}$ ampère-hour. Find how many flashes the lamp will give, allowing an average of 5 seconds for each flash.

158. Local Action. We have already seen (§§ 132, 133) that pure or amalgamated zinc is not attacked by dilute sulphuric acid unless it forms part of a voltaic cell on closed circuit, whereas common zinc dissolves in the acid at once. The explanation of the latter action is that the metallic impurities in the common zinc really constitute a large number of plates corresponding to the copper in the simple cell, so that we get a lot of little cells on short circuit. The energy furnished by the chemical action is doubtless first converted into electrical energy, but this all fritters down as local heat, and is unavailable in any other form.

Suppose, now, we fit up any kind of cell, using impure unamalgamated zinc: what happens? Well, the E. M. F. and external current are practically the same as if the zinc were pure or amalgamated, and to produce a given amount of electrical energy in the main circuit, the same amount of zinc is dissolved. But in addition to the energy of the main circuit, a large amount of useless energy is produced in the small local circuits, and this entails the consumption of

ever so much zinc to no useful end. The reason for amalgamating the zinc is, therefore, *not to augment the E.M.F. or main current*, but to save waste of zinc in producing local currents.

EXERCISE :—Describe what takes place in a Daniell cell when a rod of common zinc is employed in the porous pot.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER III.

1. In any circuit the rate of work is $V C$ watts (§ 153).

2. In a battery circuit—

Total watts developed = E.M.F. \times current.

Watts available externally = T.P.D. \times current.

Watts wasted internally = Internal drop \times current.

$$\text{Efficiency} = \frac{\text{T.P.D.}}{\text{E.M.F.}}$$

(§ 157).

3. Heat generated per second in a wire = RC^2 joules (§ 154).

4. For the same current the rise of temperature of a wire is proportional directly to the specific resistance of its material and inversely to the cube of its diameter (§ 155).

5. The reason common zinc dissolves in dilute sulphuric acid is on account of local electric circuits (§ 158).

CHAPTER IV.

CHEMICAL EFFECTS OF THE CURRENT.

159. Chemical Preliminaries. There are three acids of great importance in chemistry,¹ viz. :—

Sulphuric acid H_2SO_4 , Nitric acid HNO_3 , Hydrochloric acid HCl

It will be seen that in each of these acids the molecule consists of one or two atoms of *hydrogen* united with an element or group of elements. This element or group of elements is called the *acid radicle*; in the case of hydrochloric acid the acid radicle is the element *chlorine* (Cl), in sulphuric acid it is the group SO_4 called *sulphion*, and in nitric acid the group NO_3 called *nitron*. Neither sulphion nor nitron can be obtained in the free state; they decompose as soon as liberated from their compounds.

The characteristic property of these acids is that it is always possible either directly or indirectly to replace the hydrogen in them by almost any metal, and the resulting compound is called a *salt*. Salts derived from sulphuric acid are called *sulphates*, those from nitric acid *nitrates*, and those from hydrochloric acid *chlorides*. Subjoined is a list of the salts of chief importance in electricity :—

Zinc sulphate . . .	$ZnSO_4$	Sodium chloride } .	$NaCl$
Copper sulphate . .	$CuSO_4$	(Common salt) } .	
Ferrous "	$FeSO_4$	Mercuric chloride } .	$HgCl_2$
Ferric chloride . .	$FeCl_3$	(Corrosive sublimate) } .	
Silver nitrate . . .	$AgNO_3$	Mercuric sulphate . .	$HgSO_4$
Sodium sulphate . .	Na_2SO_4		

Zinc sulphate is derived from sulphuric acid by replacing H_2 by Zn , ferric chloride from three molecules of hydrochloric acid ($3 H Cl$) by replacing three atoms of hydrogen, $3H$, by one of iron, Fe , and so on. *Each salt clearly consists of a metal combined with an acid*

¹ There are also a vast number of others. The remarks of this chapter apply with modifications to all of them, but it is these three only that are of practical concern in relation to electricity.

radicle. Salts are generically named according to the metal they contain; thus we speak of "zinc salts," "mercury salts," etc. An acid may be regarded as a salt of hydrogen, the hydrogen playing the part of a metal.

All the salts mentioned above are *soluble salts*, that is, they dissolve in water. There are some (e.g. barium sulphate) which do not, but with such we shall have no concern.

160. Chemical Action of the Current. Voltameters. Electro-

lysis. Now consider fig. 105. P Q Q' P' is a jar or bottle containing a solution (in water) of *any salt*. In it are two platinum plates. Ah, Kl, fitted with binding screws.¹ These are connected to the high and low potential plates of a battery—a Grove of two or three, or in some cases only one cell, answers admirably. The jar with plates, etc., is called a *voltmeter*, and the plates are called *electrodes*, of which the one Ah, connected to the H.P. terminal of the battery, is called the *anode*, or *positive electrode*, or *H.P. electrode*, and the other Kl, attached to the L.P. pole, the *kathode*, or *negative electrode*, or *L.P. electrode*. When the circuit is complete as shown, a current of electricity flows from H through the leads and voltmeter in the direction of the arrows, and round to L. In the volta-

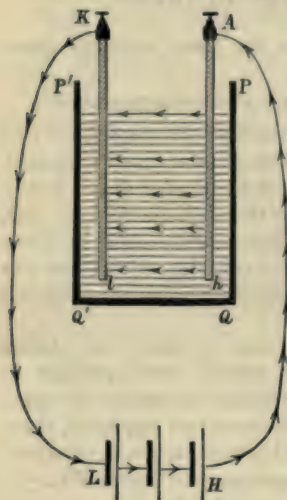


Fig. 105.

meter there is a down-gradient of potential through the liquid from the anode to the kathode, and the electricity flows down this gradient.² Now it is observed that when the current passes through the voltmeter

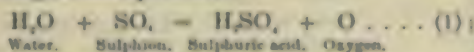
¹ In practice it is convenient to fit a cork in the bottle and to have the platinum plates attached to brass rods passing through the cork, the binding screws being fixed on top of the rods. The cork should have a small hole in it for the escape of gas.

² This may enable the student to remember to which plates the names *anode* and *kathode* are respectively applied. The term *kathode* is derived from the Greek *kata*, meaning "down"; the electricity flows *down the gradient towards the kathode*.

the salt undergoes chemical decomposition, *the metal belonging to it being deposited on the kathode, or negative electrode*. For example, if we use a solution of copper sulphate we get metallic copper on the kathode, with zinc sulphate we get metallic zinc, with silver nitrate metallic silver, and so on. If we employ an acid, then hydrogen gas appears on the kathode, the hydrogen thus playing its part as a metal (§ 159).

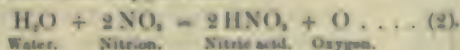
The process of thus decomposing a salt or acid is called *electrolysis*, and the solution decomposed is called an *electrolyte*.

The deposition of metal or hydrogen on the kathode is in some respects the most important feature of electrolysis. But something happens on the anode as well. If the salt be a sulphate or nitrate, bubbles of gas appear on the anode, and these when collected and examined are found to be oxygen. Taking the case of a sulphate, there is every reason to believe that what is *first liberated* on the anode is the acid radicle sulphion, but that this reacts in presence of water according to the equation :—



so that what *actually appears* is simply oxygen. This view is borne out by the fact that free H_2SO_4 gradually accumulates in the liquid.

In the case of a nitrate the action is similar : the salt first splits up into the metal and nitron, and the latter then reacts with the water, forming nitric acid and oxygen thus :—



If a *chloride* be employed, free chlorine appears at the anode, but this gas being chemically very active attacks the platinum plate, forming platinum chloride; for the electrolysis of chlorides an anode of gas coke should be employed.

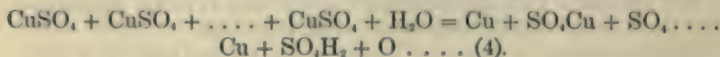
Taking the case of copper sulphate, the entire action including the liberation of oxygen may be written :—



The appearance of the metallic constituent of a salt on one of the electrodes and of the acid radicle on the other is explicable by the aid of Grothûs's theory (cf. § 146). Thus, consider the electrolysis of copper sulphate. A molecule of CuSO_4 adjacent to the kathode undergoes decomposition ; Cu is deposited and SO, liberated. This

SO_4 appropriates the Cu of the next molecule of CuSO_4 , forming a new molecule of CuSO_4 , and liberating the other SO_4 . And so on. The SO_4 thus "travels" by alternate dissociation and combination until it arrives at the anode where it reacts with the water, forming H_2SO_4 , and liberating oxygen as per equation (1).

Adopting the notation of equation (2), § 146, the entire action (3) may according to this view be written in the more expanded form:—



It should be noticed that in all cases the metal "travels" through the liquid *down* the potential gradient, *i.e.*, *with the current*, and the acid radicle the opposite way.

Fig. 106 shows a form of voltameter commonly employed for the electrolysis of dilute sulphuric acid. It consists of two glass tubes, S T E, communicating with one another near the bottom by a cross piece, and from this springs a longer tube furnished at the top with a reservoir, B. The reservoir and central tube being filled with acid, the cocks S are opened, when some of the acid rises in the tubes T, T, filling them and expelling the air. The cocks are then closed, and the electrodes E, E, connected by means of the terminals *t, t*, to the poles of a Grove battery of two or three cells. The result of the electrolysis of sulphuric acid is, as above explained, that hydrogen appears at the kathode and oxygen at the anode; these gases collect in the respective tubes. When a fair quantity of each has been obtained, if either cock be opened the weight of the acid in the central tube drives the gas out at the jet: the hydrogen can be identified by its property of burning when a light is applied, and the oxygen by re-kindling a glowing match or taper.

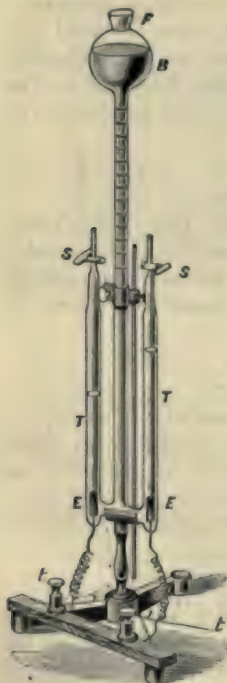
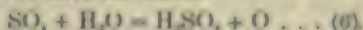


Fig. 106.

The electrolysis of sulphuric acid presents an important feature. At the kathode we have the action



This SO_4 "travels" by alternate combination and dissociation to the anode, where we have the action



Thus for every molecule of H_2SO_4 decomposed in (5) another is formed in (6), so that the quantity of sulphuric acid remains quite unaltered however long the process goes on. The result of (5) and (6) together is simply to produce the separate gases $\text{H}_2 + \text{O}$ in place of H_2O , *precisely as if we had decomposed a molecule of water*; and accordingly the proportions of hydrogen and oxygen obtained in the tubes are the same as exist in water, two volumes of hydrogen to one of oxygen. [This is shown in the diagram; the left-hand tube is the kathode, the right the anode.] On this account the electrolysis of dilute sulphuric acid is sometimes spoken of as the "electrolysis of water." But it can only be regarded as such in a fictitious sense, for if the sulphuric acid be omitted and we try the experiment with pure water no decomposition takes place. *Pure water is practically not an electrolyte.*

The electrodes of a voltameter are not necessarily of platinum, although this metal is usually preferred because it is quite unattackable either by sulphurion, nitron, or free oxygen. But it is attackable by chlorine; hence, in electrolysing chlorides an anode of carbon is employed. The material of the kathode is of less importance because the metal liberated thereat has no attacking action, but even here platinum is practically the best for most purposes. When the anode is of a substance attackable by the acid radicle or by oxygen the action is modified according to the nature and extent of attack. A simple case is afforded by the electrolysis of a solution of zinc sulphate with a pure zinc anode; here no oxygen is formed at all, the SO_4 simply attacks the zinc directly and forms ZnSO_4 , a molecule of ZnSO_4 being thus formed at the anode for every one decomposed at the kathode. Thus *the strength of the solution remains unaffected*, the kathode receives deposits of zinc and the anode is gradually eaten away, the ultimate result being just the same as if the zinc had been bodily transferred from the anode to the kathode. The same occurs in the case of copper sulphate with a copper anode

provided the copper on the latter be in a finely divided state, in which case it is readily attacked by SO_4 . The latter fact is well seen by electrolysing a solution of CuSO_4 with platinum electrodes in the ordinary way, and then reversing the current: the first part of the action deposits a finely divided layer of copper on the kathode; on reversing, the original kathode becomes the anode, and this finely divided layer of copper is eaten off, while a corresponding layer is deposited on the kathode, thus giving the appearance of bodily transference.

In any case, if an *ordinary* plate of copper be employed as the anode the action is a good deal more complicated, but consists mainly in some of the oxygen converting the copper into copper oxide, CuO , which forms a blackish coat on the plate.

EXERCISES:—1. Write down the equation for the electrolysis of dilute sulphuric acid in a form similar to (3) above for copper sulphate.

2. An electric current (which is the same in all the parts of the trough) flows horizontally in a trough filled with a solution of copper sulphate. A rod of copper is then supported horizontally in the trough, with its length parallel to the direction in which the current is flowing. How will the rod be effected by the current?

161. Battery Cells in Opposition. In fig. 107, No. 1, the cell X is in series with the battery, the H.P. terminal of the latter being

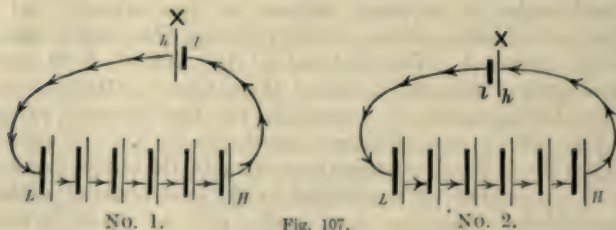


Fig. 107.

connected to the L.P. of X, and *vice versa*. But now consider No. 2: here X is said to be in *opposition* with the battery, the connexions being made the other way—that is, the H.P. plates are joined together, and likewise the L.P. When X is in opposition its E.M.F. goes *against* that of the battery (cf. Ex. 3, § 151), and not only so, but the *natural action* of X is reversed; it behaves not like a cell,

but like a voltmeter. If, for example, it were a simple cell with zinc and platinum plates, and if there were already some ZnSO_4 in the solution, instead of the sulphuric acid dissolving more zinc, some of the ZnSO_4 would become electrolysed, metallic zinc appearing on the zinc plate (the kathode), and oxygen on the platinum (the anode). Or if the cell X were a Daniell of the "zinc sulphate form" (§ 148), copper would be eaten off the copper pot and zinc deposited on the zinc rod.

If in place of a single cell X we have another battery, the same kind of thing occurs; the battery of higher E.M.F. performs its natural action, and the one of lower E.M.F. its reversed action. If both batteries have the same E.M.F. no action occurs in either of them.

EXERCISES.—1. The platinum and copper plates of a Grove and a Daniell cell are connected by a wire. Would there be a current if the zinc plates were also connected, and if so in which direction would it flow?

What reason have you for your answer?

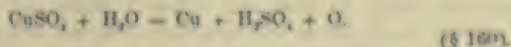
2. A single Grove cell is connected in opposition with four Daniells in series. State and explain what happens.

Also taking the E.M.F. of a Grove as 1.9, and that of a Daniell as 1.1, and the resistance of the whole circuit as 10 ohms, find the strength of the current, and the heat generated per second in the entire circuit.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER IV.

1. When a salt undergoes electrolysis, *the metal always appears at the negative electrode or kathode*—that is, the one connected with the L.P. pole of the battery; what appears at the anode is in general *oxygen*, the latter being the result of a *secondary action* between the electro-negative radicle (e.g., SO_4) and H_2O (§ 160).

The equation for the electrolysis of copper sulphate including the secondary action is —



2. When two cells or batteries are joined in opposition the one of higher E.M.F. performs its natural, and the one of lower its reversed, action, and the total E.M.F. is the *difference* of the separate E.M.F.'s (§ 161).

EXERCISES ON CHAPTERS III. AND IV.

1 (1903). One yard of thin, and one yard of thick copper wire are joined in series with a battery of Daniell cells. Is there any difference between (1) the currents in, (2) the temperatures of, the two wires?

2. The zinc and copper terminals of a Daniell cell are connected to two platinum plates which dip in a solution of copper sulphate. Describe carefully what happens at each of the platinum plates, and give the chemical equation for the action.

3. In what way will the action in the preceding question be modified (if at all) if the plates be of copper?

4 (1902). Two platinum spirals are included in the same circuit, and glow dull red when a current is passed through them. When one of the spirals is dipped in water the other glows more brightly. Explain these effects.

5. The poles of a battery are joined to the ends of a chain of alternate links of iron and copper. Does the chain acquire the same temperature throughout? Give reasons for your answer.

6. The current from a battery is passed at the same time through a thin wire, and through dilute sulphuric acid, connected in series. What will happen to the wire, and to the dilute acid, and what change, if any, will be produced in each case, by reversing the battery connexions so as to alter the direction of the current through the wire and liquid?

7. How is it that if the poles of a battery are connected by a long thin wire, the battery does not get so hot as when a short thick wire is used?

8. You have access to the terminal wires of a hidden battery. Explain how you would tell which wire was connected with the zinc and which with the platinum pole of the battery, by observing what happened when the wires were connected to the terminals of a voltmeter containing a solution of silver nitrate.

9. A current flows through a copper wire which is thicker at one end than at the other. Is there any difference either (1) in the strength of the current at, or (2) in the temperature of, the two ends of the wire? State how they differ (if they do so at all), and why.

10. Two copper plates of the same weight are connected, one with the positive (*i.e.* H.P.), and the other with the negative (L.P.) pole of a voltaic battery, and immersed side by side in a solution of copper sulphate.

If after some time the plates are removed, dried, and re-weighed, they are found no longer to weigh alike. Account for this, and explain how by the continued action of the current the equality of weight could be re-established.

11. A vertical partition of porous earthenware is fitted into a tumbler, and dilute sulphuric acid is poured into each compartment. Rods of *common* zinc and copper are placed respectively in the two compartments, and connected by a wire. State what will be observed with regard to the evolution of gas, and how the observed phenomena will be modified when copper-sulphate solution is poured into the compartment containing the copper rod.

12. It is intended to set up one hundred Grove cells in series, and by mistake ten cells are arranged in opposition to the rest: what is the relation of the potential-difference of the terminals on open circuit to what would have been obtained if the mistake had not been made?

13. Two galvanic cells are made of exactly the same materials, but in one cell the plates are much larger than in the other. What would be the effect of introducing both into a circuit so that they tend to send currents in opposite directions? Give reasons for your answer.

14. A battery of four Grove cells in series, each cell of E.M.F. 1.8 volt and resistance 4 ohm, has its terminals connected by a wire of resistance 2.4 ohms. Find (1) the current (in amperes), (2) the number of joules of work done per minute by the battery, (3) the number of calories of heat generated per minute in the wire. (1 calorie = 4.2 joules.)

Also find at what fraction of a horse-power the battery is working.

15. (1903.) What experiment would you make to determine whether the current through an incandescent lamp was alternating or continuous?

CHAPTER V

ELECTROMAGNETISM

162. Preliminary Geometrical Considerations. Before entering upon the subject of this chapter there are two points of a purely geometrical character which it is necessary to understand thoroughly : these we shall deal with in the next two articles.

163. Rotation : Clockwise and Counter-clockwise. It is frequently necessary in dealing with rotary motion to distinguish *the way a thing goes round*. When it does so like the hands of a clock, the movement is said to be *clockwise*, and when the opposite way, *counter-clockwise*. It should be noted that these terms imply that we are looking at the thing from some agreed point of view, *e.g.*, in fig. 92, p. 181, the current as indicated by the arrows is going round clockwise when we view the instrument *from the front* as shown, but if viewed from the back it would be going counter-clockwise.

The student is cautioned against the phrases "right to left" and "left to right," sometimes employed to distinguish rotation, as they are very confusing ; the hands of a clock, for example, go from left to right over the top of the face, and from right to left over the bottom ; in fact, these phrases, *when applied to rotation*, have no meaning whatever.

164. Spirals : Right-handed and Left-handed. The term spiral or helix is applied to a piece of wire or other material coiled after the manner of an ordinary spring. Now, there are two kinds of spirals distinguished by the above names and possessing an essential difference which will be learned from fig. 108. Here R shows a right- and L a left-handed spiral, and the observer is supposed to be viewing them endways ; the thick lines then represent the upper, and the thin ones the lower parts of the wire : the student can however

learn more of the matter in five minutes by winding a bit of wire on a stick, than by reading it up for an hour.

The first thing to be noticed is that each spiral possesses its own individuality, from whichever end *R* is viewed it retains the same appearance, and the same is true of *L*: we cannot make a left-handed spiral into a right-handed one by altering our point of view. Now, to see what is the essential difference between the two, imagine some insect to start at the end *A* and crawl along the coils of the respective spirals as shown by the arrows, until he reaches the end *B*; and let us stand at *A*, and looking along *A B* watch him during his journey. Then on *R* he will be seen to be moving clockwise, and on *L* counter-clockwise. The distinction, therefore, is that if

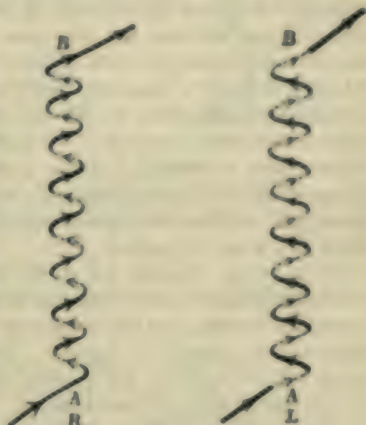


Fig. 108.

anything travel from the near to the far end of the spiral, it must, if the spiral be right-handed move clockwise, and if left-handed, counter-clockwise. This may be put into other forms of words all amounting to the same thing, but probably the most serviceable statement is that *in a right-handed spiral clockwise rotation is associated with a push, and in a left-handed one with a pull*; it is impossible to forget this if one bears in mind that all ordinary carpenter's screws are right-handed spirals, and that in driving them into the wood the screw-driver has to be turned clockwise.

165. Electromagnetism. We have already had in the electro-magnet and galvanometer instances of the production of magnetic effects by the current. The branch of the subject which deals with these effects is termed Electromagnetism, and is one of the most important especially from the point of view of the electrical engineer. The fundamental fact of electromagnetism is that *an electric current produces a magnetic field in the region round about*; this field exists

whether or no there be any iron or other magnetic material in the region, though on account of its high permeability the tendency of such material is greatly to *intensify* the field.¹

166. Law of Electromagnetic Polarity. In dealing with the magnetic action of the current, it is very often necessary to consider the relation between the direction of the current and the polarity acquired by a piece of iron subject to its influence, the direction in which it deflects a magnetic needle, or some other allied point. A general law, applicable to all such questions, is easily discovered by experiment, but is given in so many different forms by different writers that a student is often puzzled which to choose. We shall therefore give it in one form only which can be readily applied to all cases, and whether the wire carrying the current be straight or in the form of a hoop or a spiral.

To ascertain the law let us refer again to fig. 92, p. 181. Here, viewing the instrument from the front, the current is going *clockwise* round the needle, and the north pole of the needle is shown as having moved *away from the observer*. This is precisely what happens in point of fact, while if we reverse the current the north pole of the needle comes *towards* the observer. Neither is it necessary that the needle be in the middle of the hoop or even *within* the hoop at all; it may be either in front of or behind it, and the behaviour is in each case indicated by the statements just made.²

Now (§ 107), the direction in which the north pole of the needle moves is the (positive) direction of the lines of magnetic force: it thus appears that the hoop is threaded with lines of force, the law being that *when the current goes round CLOCKWISE these lines point AWAY FROM the observer, and when COUNTER-CLOCKWISE, TOWARDS him*. This is called the *law of electromagnetic polarity*, and is one of the most useful in the whole range of physical science; the student should remember it not so much in words as by mental picturing,

¹ It should be noted that a mere electrostatic charge, however great or however strong its potential, produces no magnetic field whatever. A charged copper ball or wire will neither magnetise iron nor deflect a compass needle; it is only when the electricity is *in motion* that we get these effects.

² The comparatively unimportant case where the needle is exterior to the hoop and well to the side of it will be dealt with in § 169, when it will be seen that the law we are now considering, when properly interpreted, applies to *all parts of all kinds* of electromagnetic fields.

always associating **CLOCKWISE** rotation with arrows pointing **AWAY** from him, and *vice versa*. The carpenter's screw may here again be helpful; the direction of the current is the way the screw-driver goes round, and the lines of force point the way the screw moves.

Suppose, now (fig. 109), we have a current circulating clockwise round a copper wire or strip, A B C D E F G, and introduce an iron core K'; the lines of force clearly enter the core at the end or face nearest to us and emerge at the other; hence, by the law given in § 110 the far end of the core acquires northern, and its near end southern polarity; if the current be made to go counter-clockwise the polarities are of course reversed.



Fig. 109.

167. Application of the above law to Spirals. Unless the current be extremely strong it is only possible with a single turn of wire to obtain a feeble magnetic field. To get strong effects with weak or moderate currents spirals are employed, and the effects of the several turns then add together as explained in dealing with the multiple-coil galvanometer (§ 141). The most powerful effects are obtained by winding the spirals with their coils close together and with numerous laps, in which case the wire must be "insulated," i.e., covered with cotton or some other insulating material, otherwise the current would short-circuit from one end to another and not go round the coil at all.

The law of electromagnetic polarity can easily be applied to spirals, the special point to notice being that *everything depends upon the way the current goes round*, whether clockwise or counter-clockwise; the question whether the spiral is right- or left-handed (§ 164) being merely incidental. Thus in fig. 108, in either spiral, if the current viewed from the ends A be clockwise, the lines of force (following their positive direction) will run through the spirals from the bottom to

¹ The core must be wrapped round with a piece of cloth or velvet to prevent its touching the copper, otherwise the current would short-circuit through the core instead of passing round it.

the top of the page, and if iron cores be placed in them, so as to make electromagnets (§ 168), the ends B will become north poles; the only difference will be that in R the current will work its way from A to B, and in L from B to A.

Fig. 110 will repay examination. The spiral is a left-handed one,

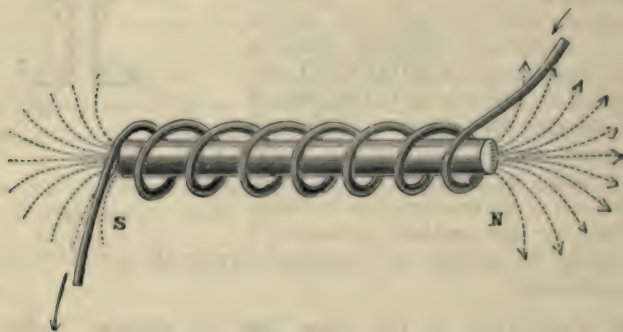


Fig. 110.

the current viewed from the right-hand end is going counter-clockwise, as indicated by the two big arrows, and in accordance with the law of § 166 the lines of force point to the right, as shown by the small arrows.¹

It should be noted that even in the absence of a core, a current-carrying spiral behaves in all respects like a magnet, the end where the lines of force emerge from its interior being its north "pole"; when suspended so as to be free to turn horizontally, it sets itself in the magnetic meridian, and its poles are attracted or repelled by the poles of a magnet or of another spiral according to the law of § 81.

EXERCISES :—1. A B is a left-handed spiral. The platinum terminal of a Grove cell is connected to the end A and the zinc to the end B, and the end A is then held a little distance west of a compass-needle. How will the needle behave?

¹ The student is strongly recommended to draw spirals as in fig. 108, rather than as in fig. 110; diagrams of the latter type, unless done in good perspective, are apt to be very confusing. On the other hand, by drawing (fig. 108) the upper parts of the coils thick and the lower thin, the nature of the spiral is obvious at a glance.

2. In the preceding question what difference will be made if a rod of (1) soft iron, (2) cast dynamo-steel, (3) hard steel be introduced into the spiral?

3 (1902). A coil of wire is wound on a glass tube in the same direction as the turns of a right-handed corkscrew. How will a compass-needle be affected if placed (1) outside, (2) inside the tube near the end where the current leaves the coil?

168. Electromagnets. These have already been considered (§ 84), and it chiefly remains (1) to accentuate the fact (§ 115) that their great power depends upon the high permeability of the iron employed for their cores, which enables them when under the influence of the current to acquire a very heavy magnetic flux, and (2) to point out certain facts regarding their winding.

In the case of a straight core wound with a single lap of wire, it is obvious that the spiral must be of the same kind all along it, otherwise there will be consequent poles (§ 96) at the points when it changes from right- to left-handed or *vice versa*. This of course means that the wire must be wound the same way throughout—it must not kink back.

Fig. 111 shows the proper way of winding a horseshoe-magnet with a single lap; here again the essential thing is that the spiral must be of the same kind throughout. In the figure it is right-handed, and if the current enter at H and leave at L, it will (when viewed from the free ends) travel clockwise round the limb A A', and counter-clockwise round B B', so that A will become a south and B a north pole. It is practically immaterial whether the central part A' C B' be wound or not; and it is usual not to do so, but to bring the wire across from A' to B', and it will be seen that the wire in passing from A' to B' must cross from the front to the back of the horseshoe.

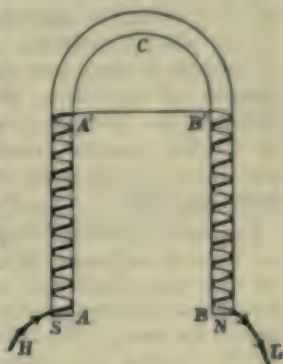


Fig. 111.

When an electromagnet has more than one lap of wire, care must be taken to wind the consecutive laps so that their electromagnetic effects co-operate with one another. Thus, if the core be straight the current must circulate the same way round all the laps, and

since the current travels from one end A to the other B along one lap and back from B to A along the next, this means that the spirals must be alternately right- and left-handed; we must therefore wind the first lap one way from A to B, and then not kink back but continue winding the second lap the same way from B to A, and so on until all the laps are completed.

Steel may be permanently magnetised by passing a current through a spiral which surrounds it; indeed (cf. § 100), this is by far the best way of making large permanent magnets.

The internal lines of force of a spiral either with or without an iron core, especially when closely wound, are practically straight lines or curves parallel to the outline of the spiral, so that they run through it, with more or less lateral leakage, very much like those of a permanent magnet (cf. fig. 64, p. 126). One of the best ways of magnetising a steel ring circumferentially is to wind it with a close spiral and pass a current, the internal lines of force then run round the ring and cause its molecules to set as in fig. 47, p. 108.

For many purposes of electrical engineering the leakage of lines of force along the sides of an electromagnet is a serious matter on the score of economy, and to minimise it the "Ironclad" type of magnet is employed in which the windings are enclosed in a cylinder of soft iron, which by its high permeability largely prevents the lines from straying into the external field. Some of the best ironclad magnets have a leakage of only about 15 per cent., whereas in an ordinary open wound one it may amount to 50 per cent.

EXERCISE:—Insulated copper wire is wound on a thin brass rod from end to end in such a way as to form a long spiral, and the ends of the rod are bent round until they touch each other. If an electric current is passed round the wire, what will be the effect on a compass-needle placed close to the spiral? Would the effect be different if the rod were of iron instead of brass? Give reasons for your answer.

169. Application of the Law of Electromagnetic Polarity to cases not yet considered. Oersted's Experiment. Bearing in mind (§ 113) that all complete lines of force are closed curves, we should expect the lines of force of a hoop or spiral, after threading through its interior, to double back externally and return into

themselves just like those of a permanent magnet, so that if a compass-needle were placed on the top of the hoop in fig. 92 (p. 181), its north pole would come *towards* the observer, or if placed at the side of the spiral in fig. 110, p. 224, its north pole would point to the left. This is exactly what happens, and it only remains to see how the law of electromagnetic polarity given in § 166 applies to such cases. At first sight it appears to be contradicted, for (fig. 92) when the current goes clockwise round the ring the lines of force outside the ring point *towards* the observer. But now look at fig. 112. Let AB be the hoop carrying a clockwise current, and consider the point P . The field at P is mainly due to the upper part HK of the hoop, and what we must regard is not the rotation of the current round the whole hoop, but its rotation *relative to P* . We therefore

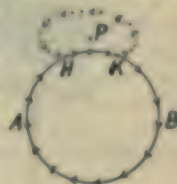


Fig. 112.

imagine the current after traversing HK to continue its course round P along the dotted line, and it is at once seen, as shown by the arrows, that its rotation relative to P is *counter-clockwise*, so that the lines of force point towards us in fulfilment of the law. Similar remarks apply to the field at the side of a spiral. An important case to which the same idea applies is that of a straight wire. Thus in fig. 113, AB is a straight copper wire

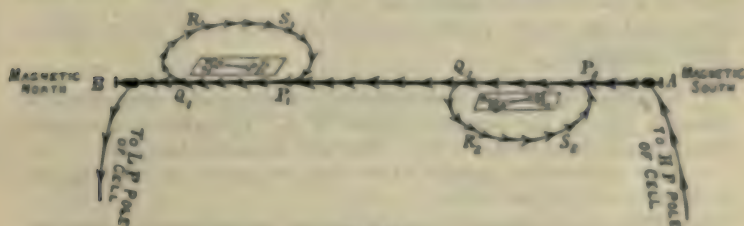


Fig. 113.

set horizontally in the magnetic meridian with a current flowing along it from south to north, and we are viewing it from the west side. The compass-needle at the left of the diagram is above the wire and the imaginary circuit, $P_1 Q_1 R_1 S_1$, is clockwise, so that the north pole of the needle moves eastward; the needle

on the right is below the wire, the imaginary circuit, P, Q, R, S , is counter-clockwise, and the north pole moves westward. This experiment is interesting from the fact that it is the one originally made by Oersted, of Copenhagen, in 1819, whereby the magnetic action of the current was discovered.

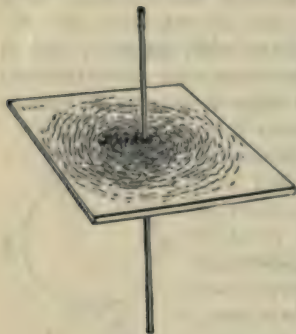


Fig. 114.

If (fig. 114) we take an horizontal piece of cardboard through which passes a vertical wire carrying a current, sprinkle iron filings on the card, and gently tap it, the filings will arrange themselves in circular curves round the wire.

These curves map out the

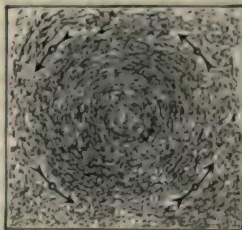


Fig. 115.

lines of force of the field, and their direction is determined by the law of electromagnetic polarity, as above interpreted; this is better shown in fig. 115; the current is supposed to be coming up through the centre of the card in a direction perpendicular to its plane, and the arrows point along the lines of force at the several places indicated.

1. A vertical copper wire is mounted in a frame, and a compass-needle placed a little to the (magnetic) north of it. A current is now passed along the wire from bottom to top. How will the needle behave?

2. Same as preceding question except that the needle is magnetic *west* of the wire (cf. 2nd part of Ex. 1, § 123).

3. (1899.) A wire through which a current may be passed is stretched horizontally in a certain direction immediately over the centre of a compass-needle. When a weak current flows the needle is not affected, but if the current be sufficiently increased the needle swings round and its north end points southwards. Explain this, and state in what direction the wire is stretched.

4. (1900.) The ends of a brass rod on which a steel ring has been slipped are joined to the poles of a battery. Is the steel ring magnetised

by the passage of the current through the rod? How will you test whether it is or not?

5. (1903.) A straight wire carrying a current is placed over a thin rod of iron (1) parallel to the iron, (2) at right angles to it. Is the iron in either case magnetised? Give reasons.

6. Prove the following minor rule for the lines of force due to a straight current. Look along the wire; then if the current is flowing away from you the positive direction of the lines of force is clockwise, if towards you it is counter-clockwise.

7. A number of galvanic cells are connected together in a row so as to form a battery. This row is laid on a table so as to lie N. and S. The zinc is to the N. The poles of the battery are connected together by a wire, which passes from one pole up one wall of the room, across the ceiling, and down the opposite wall to the other pole of the battery. How will a magnetic-needle be affected which is placed under the table and just below the battery?

170. Astatic Galvanometers. In order that a galvanometer may be delicate, it is necessary to arrange matters so that the needle may be affected as *much* as possible by the current, and as *little* as possible by other influences. One way of promoting these ends is to employ many turns of wire, and another is to suspend the needle by a fine silk thread so as to avoid the friction of a pivot. Finally, we must abolish as much as possible the earth's action, for which purpose we

employ an astatic needle (§ 131); we thus get an *Astatic Galvanometer*. Fig. 116 shows the method of winding. The simplest ar-

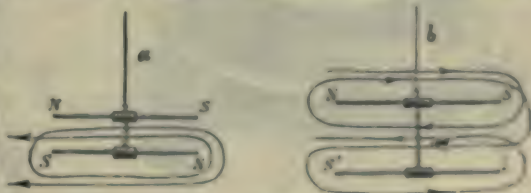


Fig. 116.

simplest arrangement is indicated in the left hand diagram, *a*; here the wire encircles the lower needle only. As drawn, the current relative to the lower needle (§ 169) is counter-clockwise, so that its north pole is urged towards us; at the same time the current relative to the upper needle is clockwise, and its north pole is therefore urged away from us: both agencies therefore urge the needle as a whole the same way. A better mode of winding is shown in the right-hand diagram, *b*; the

wire encircles both needles, but in opposite ways, so that the current flows clockwise round one and counter-clockwise round the other; the effect is similar to that in *a*, but stronger, because, other things the same, the upper needle is in a more powerful magnetic field.

Fig. 117 exhibits Nobilis' Astatic Galvanometer. The needle is suspended by a fine silk thread from an adjustable screw; the coils

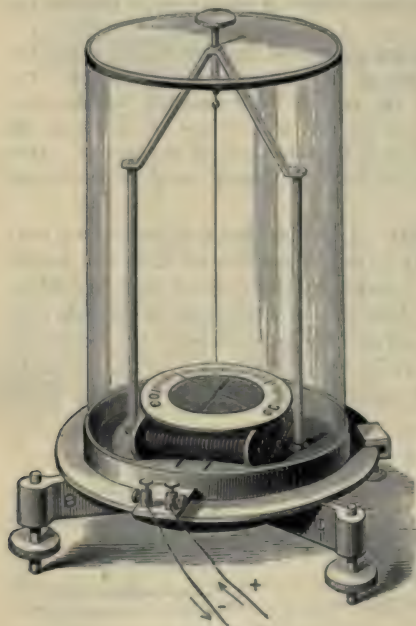


Fig. 117.

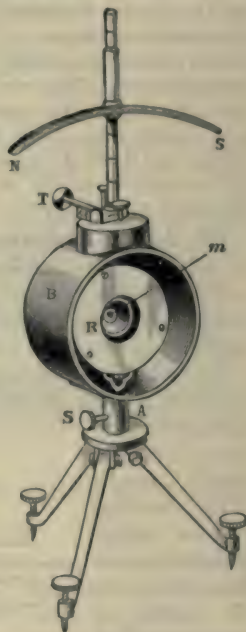


Fig. 118.

encircle the lower needle only, and the upper carries a pointer, which travels over a cardboard scale.

Fig. 118 shows Lord Kelvin's Astatic or Mirror Galvanometer. It has a number of elaborate adjustments, which render it beautifully sensitive, and yet very easy to work with. Instead of a pointer, the needle is attached to a small mirror, *m*. Fig. 119 indicates the method of using the instrument. It stands on a firm shelf, and in front of it

is placed a paraffin lamp and graduated scale. When no current is passing, the mirror faces the scale. A narrow beam of light shines through a slit below the scale, and, following the direction of the lower dotted line, is reflected along the upper, and falls on the middle, or "zero," of the scale. If a current be now sent through

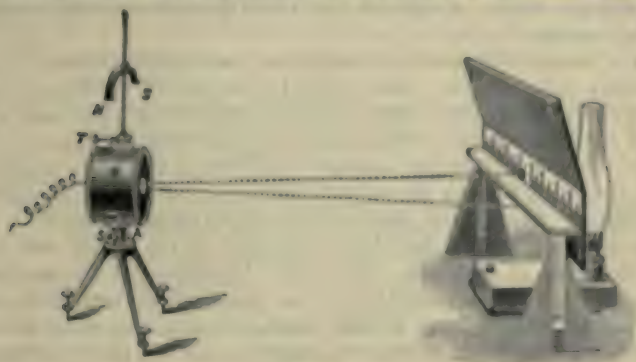


Fig. 119.

the galvanometer, the mirror swings either to the right or left, the "spot of light" travels along the scale, and unless the current be excessively weak, goes off the scale altogether. This instrument enables us to detect and measure accurately currents of inconceivable minuteness—say, a millionth of an ampère.

171. Detection of Electrostatic Currents. Whenever two conductors in an electrostatic state, but at different potentials, are connected, a momentary current flows. If, as in an electric machine, we *maintain* a P.D., the current becomes continuous. Whether continuous or not, such currents may be appropriately termed "electrostatic currents," to distinguish them from the "electrodynamic currents" furnished by batteries, dynamos, etc. In the same way, potentials obtainable by electrostatic methods may be called "electrostatic potentials," while those furnished by batteries, etc., are called "electrodynamic potentials."

We have seen (§§ 71, 135) that electrostatic potentials are vastly stronger than electrodynamic; a metal ball beaten with fur may readily attain a potential of 50,000 volts, and a good plate machine

one of 100,000, while a Grove cell gives less than 2. The difference between the currents is precisely the reverse—electrostatic currents are vastly *weaker* than electrodynamic. Thus, while a moderate-size Grove cell on short circuit may easily furnish eight or ten ampères, it is much if a good plate machine will give $\frac{1}{1000}$ ampère. A Leyden jar will give more. A charged metal ball may give something under $\frac{1}{1000}$ ampère.

It is therefore impossible to detect an electrostatic current by any ordinary galvanometer: even a big Leyden jar will produce not the least movement of the needle. But the detection is quite easy with Lord Kelvin's astatic. If we connect one of its terminals, A, with the positively charged prime conductor of even a bad plate machine, and the other, B, with the rubber or the gas-pipe; then on slightly moving the handle, the spot of light travels along the scale in the same direction as if A had been connected to the copper and B to the zinc plate of a simple voltaic cell. If, instead of the machine, we employ a charged metal ball, the spot will move slightly, the movement being in one or the other direction, according as the charge on the ball is positive or negative. If we place a charged Leyden jar on an insulating stool, and then connect its outer coat to one terminal of the galvanometer and its knob to the other, the "spot" will move very decidedly; in fact, unless the jar be very feebly charged, there is some danger of damaging the instrument.

The student should note carefully that these experiments, as well as those with the condensing electroscope (§ 140), established beyond doubt the essential identity of the things with which we deal in electrostatics and electrodynamics.

EXERCISE:—Describe experiments whereby it is proved that the terminals of a voltaic cell differ electrically in the same way as the prime conductor and rubber of a frictional machine.

***172. Mutual Magnetic Action in Terms of Magnetic Flux: Maxwell's Law.** Consider the following simple experiment: Float a cork on water, place on it a small bar magnet or magnetic-needle, A, and hold another bar magnet, B, horizontally, with its north pole near A. Then A first turns round, so that its south pole faces the north pole of B, and then moves up to and touches it. Of course this follows from the elementary law of § 81. But there is another way of looking at it. When the movable magnet, A, has attained its final position, its own lines of force point in as nearly as possible the same direction as those of the

fixed magnet, B, and it is also in the part of the external field where B's flux is densest, so that as much as possible of B's flux passes through A. Now we have here a principle which applies to all kinds of magnetic action, whether due to magnets or electric currents, or both, and which covers cases hardly within the domain of the elementary law. This principle is known as *Maxwell's Law*, and may be thus stated:—*When two circuits¹ mutually act on one another, they tend to place themselves that:—*

- (1) *Their respective lines of force point as nearly as possible in the same direction.*
- (2) *Each circuit encloses as much as possible of the other's flux; or, in engineering phraseology (§ 112), as many as possible of the other's lines of force.*

To these clauses should be added:—

- (3) *That if the circumstances be such as to compel the two sets of lines of force to point more or less in OPPOSITE directions, each circuit tends to embrace as LITTLE as possible of the other's flux.*

For example, in the foregoing experiment if we place the movable magnet, A, with its north pole facing the north pole of B, and then by some means prevent its turning round, while still leaving it free to move bodily, it will recede from B into the part of the field where B's flux is lightest.

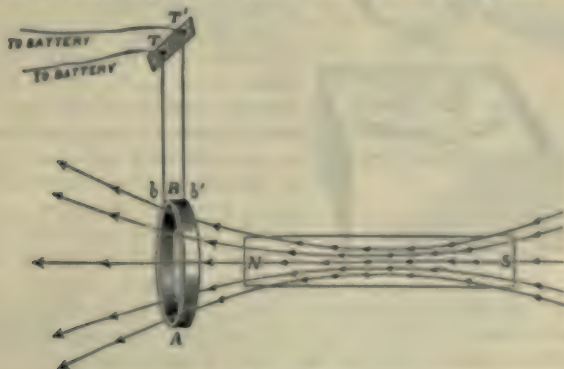


Fig. 120.

Let us now consider some other phenomena in the light of Maxwell's Law:—

In fig. 120 AB is a squat spiral of fine copper wire whose ends are

¹ The word circuit is here used broadly to denote either a conductor carrying a current, or a magnet.

suspended from terminals T, T' on a wooden stand.¹ A bar magnet is placed horizontally and pointing towards the spiral; supposing its north pole towards the left, the lines of force also point towards the left as shown, and the flux is densest at the centre of the magnet, more or less lateral leakage (§ 113) occurring between the centre and the ends. We now pass a current round the spiral. Suppose that when viewed from the right it goes clockwise, then (§ 166) *its* lines of force also point to the left, so that clause (1) of Maxwell's rule is *already* satisfied, and it simply remains for the spiral to obey clause (2), which it accordingly does by shooting itself along the magnet and coming to rest at the middle, where it embraces as much as possible of the magnet's flux.

If (re-starting in the position shown in the figure) we now reverse the current, the lines of force of the spiral will point opposite to those of the magnet, and in compliance with clause (1) the spiral will first twist round so as to face the other way and then shoot on as before. But if it be forcibly prevented from twisting round while still leaving it free to move to

and fro, then it becomes a case of clause (3), and the spiral moves as far away from the magnet as it can get, so as to embrace as *little* as possible of the magnet's flux.

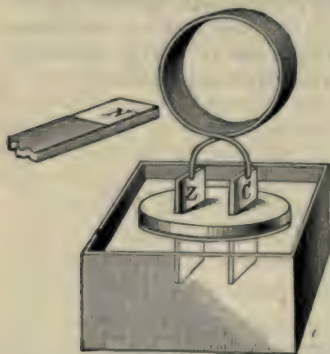


Fig. 121.

Fig. 121 shows a somewhat simpler apparatus for producing the same effect; it is known as De La Rive's floating battery. A zinc and copper plate are fitted in a cork and connected to the ends of a flat spiral, the cork is then floated in dilute sulphuric acid; a current circulates round the coils of the spiral, and, when a magnet is held near it, it behaves like the spiral in fig. 120. Also if we place

two such "batteries" in the same vessel, they will set themselves with their coils parallel and their currents circulating in the same direction.

It should be noted that the fact that in any assigned case the flux through a circuit can be different in different positions implies that as the circuit changes from one position to another it *cuts* the lines of force; in fact, the change of flux is commonly spoken of by engineers as the "number of lines of force cut" or the "number of cuttings." In fig. 120,

¹ The suspending portions, T, T', of the wire should be much longer than in the diagram, so as to allow the spiral plenty of freedom.

the cuttings between the end and middle of the magnet are manifestly due to lateral leakage: if there were no such leakage the spiral would move up to N, but no farther. In a circumferentially magnetised ring there is no leakage, and the spiral would remain quite stationary whether threaded on one of its limbs or placed so as to be capable of sliding over the entire ring.

EXERCISES:—1. A narrow glass tube is wound with a spiral of wire and a current passed. A neutral knitting-needle is then placed with one end just inside the tube. On letting go it shoots right in, and stops when its middle coincides with the middle of the tube. Explain this.

2. There are two copper rings, A and B, both carrying a current, of which A is fixed and B movable. They are placed with their planes vertical and parallel, and their currents circulating in opposite directions. State and explain the behaviour of B (i) when it is free to move in any manner, (ii) when it is free to move to and fro, but not to turn round.

SUMMARY OF MOST IMPORTANT POINTS IN CHAPTER V.

1. Distinction between clockwise and counter-clockwise rotation (§ 163), and between right and left-handed spirals (§ 164). In a right-handed spiral clockwise rotation is associated with a push, and in a left-handed one with a pull.

2. Law of Electromagnetic Polarity, viz., that when a current goes round clockwise the lines of force point away from the observer, and when counter-clockwise, towards him (§ 166). Application of this to spirals (§ 167) and to straight circuits, etc. (§ 169).

3. Proper way of winding electromagnets (§ 163).

4. Construction and delicacy of Astatic Galvanometers (§ 170).

5. Two ways of proving the identity of the things dealt with in Electrostatics and Electrodynamics, viz. (1), by the Condensing Electro-scope, (2) by the Astatic Galvanometer (§§ 140, 171).

6. Maxwell's Law, especially its first clause (§ 172).

EXERCISES ON CHAPTER V.

1 (1899). Part of a wire is coiled round the bulb of a mercurial thermometer, and another part round an iron rod. How are the

thermometer and rod affected when a current is passed through the wire, and how are the effects altered by reversing the direction of the current?

2. (1901.) If you were asked to show that when the two coatings of a charged Leyden jar are connected by a wire, a current of electricity of the same nature as that produced by a voltaic cell passes through the wire, how would you proceed?

3. (1901.) A compass-needle is placed at the centre of a vertical ring of wire. When the plane of the ring lies east and west the needle is not necessarily deflected when a current is sent round the ring, but when the plane of the ring lies north and south the needle is deflected violently. Explain this.

4. (1901.) Describe the construction of an astatic galvanometer. Give a sketch of the coils and needles in position, and explain how to find the direction of the current through the instrument by observing the direction of the deflection.

5. A rod of soft iron is placed upright on a table. Its upper end is surrounded by a coil of insulated wire which does not touch the rod. When a strong current goes through the wire, the iron rises in the coil. Explain why.

6. One terminal of a astatic galvanometer having a coil made of a great many turns of fine wire, is connected with the prime conductor of an electrical machine, and the other terminal with the rubber of the same machine. When the machine is worked the needle of the galvanometer is deflected. Show how the direction of the deflection depends upon which terminal of the galvanometer is connected with the conductor and which with the rubber.

7. A long copper wire covered with silk is wound several times round an iron rod. On connecting the ends of the wire, one with each terminal of a Daniell's battery, the iron rod becomes a magnet. How does the direction of magnetisation of the iron (or the position of its north-seeking and south-seeking poles) depend upon how the copper wire is wound, and which end of it is connected with the copper end of the battery? Give a drawing.

8. Two compass-needles are arranged near each other so that both point along the same straight line. A wire connecting the platinum and zinc ends of a battery is stretched vertically half-way between the needles. How will the current in the wire affect the needles, and how will the result

depend upon whether the platinum terminal is connected with the upper or lower end of the wire respectively?

9. A wire lies east and west (magnetic), immediately over a compass-needle. How is the direction in which the needle points affected when a *strong* current flows through the wire (1) from west to east, (2) from east to west?

10. A gutta-percha-covered copper wire is wound round a wooden cylinder, A B, from A to B. How would you wind it back from B to A, (1) so as to increase, (2) so as to diminish, the magnetic effects which it produces when a current is passed through it? Illustrate your answer by a diagram drawn on the assumption that you are looking at the end B.

11. A current is flowing through a rigid copper rod. How would you place a small piece of iron wire with respect to it so that the iron may be magnetised in the direction of its length? Assuming the direction of the current, state which end of the iron will be a north pole.

12. A strong electric current flows through a copper wire which passes through the centre of an iron ring, and is at right angles to the plane of the ring. Describe the magnetic state of the ring.

13. Describe an experiment which shows that in the charging of a condenser by contact of its plates with the poles of a strong battery, there is a current of electricity. Explain why this current is only momentary.

14. A current of electricity is passed through a long, coiled conducting wire. Draw a diagram illustrating the form and directions of the lines of force within and without the coil.

15. Two magnets are firmly attached at right angles to a wire which is suspended so that the magnets can rotate in a horizontal direction. The magnets are parallel and like poles are turned in the same direction. You are supplied with a flexible wire through which an electric current is passing, and are required to determine (without touching the magnets) whether they are of equal strength. Describe and explain your procedure.

16. A long straight wire is stretched on a table in the direction of the magnetic meridian, and a dip circle, with its plane parallel to the magnetic meridian, is placed on the table near to the wire and on the west side of it. Will the dip of the needle be altered when an electric current is passed along the wire from south to north? and if so, how? Give reasons.

17. Two spirals of insulated copper wire are constructed so that one can slide freely inside the other. They are placed horizontally with one end of one just inside one end of the other, and independent currents passed through them. Explain what will happen according as their currents circulate in the same or in opposite directions.

18. (1901.) Copper and platinum wires of the same length and section are wound on two glass tubes, the coils being in every respect alike. If they are connected together, and to a battery, so that the same current passes through both, explain how they will differ from each other in respect of (1) their action on a compass needle, (2) their rise of temperature.

ANSWERS TO THE EXERCISES.

NOTE.—A few answers are omitted as being either sufficiently obvious or too lengthy. In many instances the conclusions only are given, but in a few of the more difficult the reasoning is briefly added, and when absent should be carefully supplied by the student. Many of the answers are of necessity given in mere outline, and should be amplified.

PART I.—ELECTROSTATICS.

- § 15. (1) Practically nothing. (2) The carret receives a small contact charge. (3) Practically nothing. (4) Partial local discharge of rod.
- § 16. No.
- § 18. The pith ball will be attracted by the glass rod, and if the electrification of the latter is fairly strong, will, after touching it, be repelled.
- § 22. (1) Repulsion. (2) Attraction.
- § 23. (1) The india-rubber attracts the glass. (2) The brush repels the brass.
- § 25. (1) Nothing. (2) Attraction. (3) Attraction.
- § 28. It will be attracted.

EXERCISES ON CHAPTER I.—ELECTROSTATICS.

1. See § 20. 2. Copper, iron, water, wood, silk, fur, glass, air.
3. Hold the rod near the ball, and see if it is repelled after touching (cf. § 16). 4. See § 12. 5. The pair suspended by silk threads will first be attracted upwards to the conductor, and will afterwards be repelled from it, and from each other; the other pair will be repelled from each other without first being attracted to the conductor.

- § 32. (i) Nothing. (ii) Nothing. (iii) Potential becomes zero. (iv) Charged shared in such a way as to produce the same potential in both conductors. (v) Same as (iv). (vi) Flow of electricity from the one of higher potential. (vii) Nothing.
- § 35. They will at once collapse, for by Poisson's principle the potentials of A, B, the leaves and netting all become equal.

- § 39. 2. Beat an insulated metal ball with india-rubber and hold it over the electroscope; if the leaves diverge more, they are at positive potential. But if they diverge less, discharge the metal ball, beat it with fur, and again hold it over; if now they diverge more, they are at negative potential.
- § 45. 1. If B were removed first the negative charge previously induced on A would escape to earth; for if it did not it would maintain A at free negative potential, which is impossible, since the potential of an earthed conductor is zero.
2. No. 3. No.

EXERCISES ON CHAPTER II.—ELECTROSTATICS.

1. (1) Diverge at + potential. (2) Collapse. (3) Diverge at - potential.
2. Squeeze the bag, then turn on the cock, then turn it off again, and lastly cease squeezing.
3. (1) Positive. (2) No; it was weaker (less strongly negative), on account of the + charge acquired by B.
6. (1) Diverge. (2) Collapse. (3) Diverge again.
7. First give B a negative induced charge by means of A, as in § 45, then set A aside and give the electroscope a positive induced charge by means of B.
8. (1) They will both diverge to the same extent because by Poisson's principle they both have the same (induced) potential. (2) When touched by the finger both acquire potential zero and their leaves collapse, but when the finger is removed both acquire the same (free) - potential and again their leaves diverge, both to the same extent.
-
- § 47. Up-gradient as we near the metal; at the metal itself we are at the top of the gradient, and remain on a level all through the interior until we approach the level of the mouth; we then begin to go down, until at a distance of, say, a couple of feet the potential is practically zero.
- § 50. 1. Nothing; there is no inductive displacement, and both balls remain perfectly neutral.
2. (i) Diverge. (ii) Diverge still more.
3. Yes, opposite to the cage.
4. No.
- § 51. The charge of the shot will be completely emptied into the cylinder, so that it will acquire a - charge, while the vessel will receive no charge at all.
- § 52. 2. (i) Do not diverge. (ii) Diverge at + potential. (iii) Diverge at - potential.
- § 53. 1. (i) Diverge. (ii) Collapse.
2. (i) They collapse. (ii) They remain diverged.

- § 57. Their divergences will become equal.
 § 58. The one surrounded by air.
 § 59. 1. (i) Divergence very slightly decreased. (ii) Divergence considerably decreased. (iii) Divergence becomes the same as it was to begin with.
 2. The hand, being an earthed conductor, weakens the potential of the leaves. An insulated metal ball would do so to a less extent.
 3. If the body were neutral, it would in any case cause slight collapse by weakening the potentials of the leaves.
 § 61. 47,040.

EXERCISES ON CHAPTERS II. AND III.—ELECTROSTATICS

1. (1) Very slight decrease of divergence. (2) Increase. (3) Decrease; If A is earthed still greater decrease.
2. See § 55.
3. (1) No divergence. (2) Divergence.
5. They remain at rest; see § 50.
6. See § 51.
7. See fig. 13, and apply the knob test (§ 40) to the ends A and B.
8. See § 52.
10. (1) A conductor at a certain potential. (2) Another at *lower* potential.
11. Hold a strongly + charged body near, so that (§ 42) the potential of the conductor is +.
12. Suppose the electrified body +. Then (a) potential of electrified body lowered very slightly (§ 59), and that of unelectrified conductor raised (§ 41); (b) of electrified body lowered considerably, and of unelectrified conductor unaltered.
13. From the symmetry of the arrangement it follows that B and C are at the same potential, and therefore, by Poisson's principle, when connected by a wire *nothing whatever happens*. Of course, by inductive displacement the sides of both B and C farthest from A become charged one way, and the sides nearest to A the opposite way; *but it is the potentials, and not these local charges, that determine the flow*. The points of B and C where the wire touches are quite immaterial.
14. In the first case, yes; in the second, no. In the first case the netting acquires a certain potential and the leaves a *weaker* induced potential; the second case is practically that discussed in § 50.
15. (i) The third sphere receives equal and opposite impressed potentials from the other two, and its actual potential is therefore zero. (ii) By inductive displacement the side of the third sphere nearest the + sphere becomes negatively charged, and the other side positively.

- § 67. 2. The density is greatest on the part of the pot nearest the ball, and least on the part farthest away.
 3. It will probably be *least* at the point.
 4. Touching the uncharged ball reduces its potential to zero, and thus steepens the potential — gradient between the two.

EXERCISES ON CHAPTER IV.—ELECTROSTATICS.

1. The charge must be free, and the sphere a long way from other conductors, and surrounded by nothing but dry air. There *are* other conditions under which it is true, but these are what is commonly intended.
2. (1) Orange acquires a charge of the same kind as that of the body. (2) Of the opposite kind.
3. (1) B partly discharged. (2) B almost completely discharged.
5. See §§ 67, 68.
6. No change until the needle gets outside the pail, then fairly rapid discharge (§§ 67, 68).
7. See § 67, especially the case considered in fig. 27.
8. This is often loosely said to prove that the *electric density* is diminished by uncoiling the chain; in reality, however, what it shows is that the *potential* is diminished (§ 36), or (since the total charge remains unaltered) that the electrostatic *capacity* is increased. As a matter of fact the density is diminished, but to prove this we must have a different experiment, viz., one with a proof plane and a small pot standing on another electroscope (§ 65).
9. Nil.
11. (1) No difference in densities, (2) Potential of B weaker than that of A (§ 58).
12. Very similar to question 7; the diagram should be drawn according to the method of fig. 25.

-
- § 75. 1. No difference whatever.
 2. No.
 3. No.
 4. After having made the attempt as described in § 74, connect the knob and outer coat by insulated discharging tongs when no appreciable spark will be obtained.

EXERCISES ON CHAPTER V.—ELECTROSTATICS.

4. The capacity of the small jar is less than that of the big one. Hence by the formula $Q = CV$ the potential of the small jar is (supposing the charge +) *higher* than that of the big one; the spark then passes in accordance with Poisson's principle.

5. No effect. The machine gives a + charge on the prime conductor, and a - charge on the inside of the chamber; but the total charge (§§ 25, 55) is nil. Also (§ 52) the potential of the chamber is the same as if this total charge belonged to it "freely."
7. (Cf. § 76). The inner coat of the second jar becomes negatively charged.

PART II.—MAGNETISM.

- § 80. In a horseshoe magnet fig. 35, the poles are at N and S; the simplest way is to suspend the magnet by a thread tied to the middle of the bend when it hangs with its poles downwards and comes to rest with N towards the north.
- § 86. Diminish it.

EXERCISES ON CHAPTER I.—MAGNETISM.

1. See § 82.
2. A temporary magnet, its ends of opposite polarity to those of the bar magnet respectively below them.
3. The ball falls off; the inductive action of the south pole on the ball counteracts that of the north pole (§ 85).
4. (1) Falls off; cf. preceding question. (2) The inductive action of the south pole assists that of the north, and the latter holds the ball tighter. But at the same time the south pole attracts it, and if near enough may pull it off, its weight of course assisting.
5. See § 82.
6. No, it will be less; see § 85.
7. It will move towards the iron; § 86.
8. The deflection becomes less; see § 85.
9. Hold a compass-needle near the rod, and bring it gradually downwards until a point is found which attracts indifferently either pole of the needle; this point (§ 88) is the middle of the rod.

- § 98. 2. No; the molecular rigidity of the steel would prevent its molecular chains opening as shown in the keeper fig. 42, No. 2.
- § 99. 3. Test the ends and also intermediate points by a compass-needle as in § 82.

EXERCISES ON CHAPTER II.—MAGNETISM.

4. See last paragraph of § 90.
6. If at the middle the two fractured faces will have the same polarity, if elsewhere opposite.

8. The steel rod will become magnetised, but the iron will, as soon as the magnet is removed, become neutral: the rest follows from § 82.
10. This is practically a case of circumferential magnetisation (see § 92).

- § 109. 1. See fig. A appended.
 2. See fig. B appended.
 3. See fig. C appended.

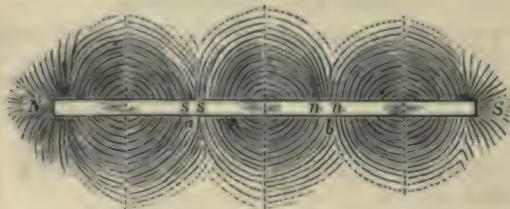


Fig. A.

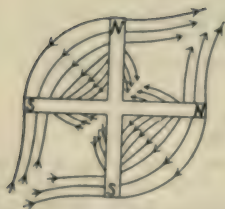


Fig. B.

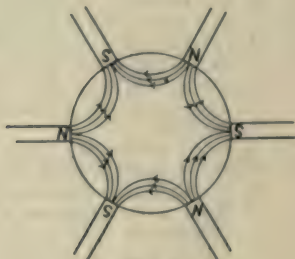


Fig. C.

- § 110. Both its ends will acquire southern and its central portion northern polarity.
- § 116. 2. The deflection is less with the iron. We may regard it from two points of view; we may say (1) that by induction each end of the bar acquires polarity opposite to that of the end of the magnet which it overlaps, so that the two oppose each others' action in the external field; or (2) that the lines of force that issue from the north pole of the magnet have to work their way round into its south pole, and according to the principle of least reluctance, make a sharp turn round through the iron bar rather than taking a journey through the air-field.

3. This is best explained from the point of view of flux. When the iron is on only one pole, the lines of force in travelling from the north to the south pole of the magnet would not "gain much" by going through it, as they still have a considerable air-space to traverse, and accordingly they do not crowd much into it, or if they start to go through it, leak out at the sides; but when the iron connects both poles they can altogether avoid an air-journey by going through it—accordingly they crowd into it, producing a much denser flux and correspondingly greater attraction.

§ 117. The aperture of the pipe is screened from the magnetic action, and very few filings collect over it.

EXERCISES ON CHAPTER III. *MAGNETISM.*

1. Diminished. See § 116.
2. Figs. 65, 66, will afford suggestions. There are several cases depending upon how the poles are arranged.
3. Cf. fig. 67.
4. (1) Soft iron being highly permeable draws practically all the flux into itself, so that the filings over the air-space beyond the poles will cease to arrange themselves in definite curves. (2) The permeability of ordinary steel is fairly high, but distinctly less than that of soft iron, so that more of the flux will be left in the air-space and there will still be some curves over it, though fewer than before. (3) The permeability of copper being practically the same as that of air, the copper will have no effect.
5. In order that the lines of force emanating from the rubbing pole may pass through the bar in the direction of its length, and so tend to send the molecules as nearly as possible lengthways.
6. (i.) The needle will be screened as in Fig. 72 and be practically unaffected by the magnet. (ii.) Here again the needle will be screened. This is easily explained by the principle of least reluctance (§ 116); the lines of force of the magnet have to get from its north to its south pole, and it will be "less trouble" for them to work their way round through the iron than through the external air.
7. The field will be gradually strengthened until when the magnets touch it becomes equal to the internal field; compare the effect of gradually approaching the opposite poles of two bar magnets.

§ 123. 1. (1) The needle will not move. (2) Everything depends upon the relative strengths of the earth's horizontal field and the field due to the magnet at the place where the needle is located. If the earth's field is the strongest the needle will not move, but if the magnet's field is the strongest it will make a complete half-turn and set with its north pole pointing magnetic south.

- § 127. At any place on the magnetic equator.
 § 130. 4. (1) The north pole of the compass is deflected, more or less towards the west. (2) The needle is either unaffected or turns with its north pole towards the south, according to the strength of the polarity acquired by the mast.

EXERCISES ON CHAPTER IV.—*MAGNETISM.*

1. See § 122.
3. See § 124.
5. See §§ 124, 129.
8. Supposing that by "east" and "west" is meant *magnetic* east and west, it is in the original position simply attracted owing to inductive action from the needle, while in the final it is repelled, A having become a north pole by the inductive action of the earth.
9. Dip decreased in both cases and in either hemisphere.
10. See § 116.
11. Compass should of course point (magnetic) north. In (1) it deviates somewhat towards the west, in (2) towards the east.
12. (1) Suspend so that it can turn horizontally, and note the direction along which it sets. (2) Suspend so that it can turn *freely*; then, if you are in the northern hemisphere, the north lies in the direction of the end that slopes downwards. If you don't know which hemisphere you are in, you must make preliminary inquiries.
15. As explained in § 125 it sets vertically by virtue of the vertical component of the earth's force, but at the magnetic equator this vertical component is nil.
16. See § 123.
17. Increased in both hemispheres.
18. Cf. latter part of § 131.
19. It will be astatic.

PART III.—ELECTRODYNAMICS.

- § 134. 2. Precisely the same action as in question 1, except that the current, instead of going through the wire, will pass direct from the copper to the zinc at the place where they touch.
- § 135. B has three times the resistance of A.
- § 136. 1. 3 amperes.
 2. $66\frac{2}{3}$ ohms.
 3. $2\frac{1}{2}$ volts.

- § 138. 1. (1) $C = \frac{1}{2}$ ampère, T.P.D. = 9 volts.
 (2) $C = 1\frac{1}{2}$ ampères, T.P.D. = 3 volts.
 2. (i) $\frac{1}{2}$ volt, (ii) $1\frac{1}{2}$ volts.
 4. (i) $\frac{1}{2}$ ampère, (ii) $12\frac{1}{2}$ volts, (iii) $6\frac{1}{2}$ volts, (iv) $6\frac{1}{2}$ volts.
 6. No. By § 137 the E.M.F. is not altered; also the resistance is not altered, and therefore by Ohm's law the current is not altered.
 7. 299 ohms. The working is as follows: Let E denote the E.M.F. of the battery, then by equation (1a) § 138 we have $I = \frac{E}{1 + 6}$; $\therefore E = 6$. Next let x denote the resistance of the wire CD, then again by equation (1a), $\frac{1}{11} = \frac{6}{1 + x}$; $\therefore 1 + x = 300$;
 $\therefore x = 299$.
 8. 108 volts.
 § 141. 1. 0.2 ampère.
 2. The resistance of the coil is $2\frac{1}{2}$ times that of the rest of the circuit. Proceed thus: Let E be the E.M.F. of the cell, x the resistance of the coil, and R that of the rest of the circuit including the cell and galvanometer. Then by Ohm's law the current without the coil is $\frac{E}{R}$, and with the coil $\frac{E}{R + x}$. Hence by the terms of the question $\frac{E}{R} \div \frac{E}{R + x} = \frac{1}{2}$; i.e., $\frac{R + x}{R} = \frac{1}{2}$;
 $\therefore 3R + 3x = 10R$; $\therefore 3x = 7R$; $\therefore x = 2\frac{1}{2}R$.
 § 144. Nil.
 § 151. 1. 28 volts.
 3. 2c; the cell put in the wrong way is said to be in "opposition" to the others, and its E.M.F. subtracts instead of adding.
 5. It will be less, because as explained in § 138 the T.P.D. on closed circuit is less than the E.M.F.
 6. $1\frac{1}{4}\frac{1}{2}$ ampère; about 1005 times as great.
 7. $\frac{1}{2}$ ampère; nearly 10 times as great.
 8. $\frac{1}{2}$ an ampère; 6 volts.
 9. One-third as great.
 10. Compare the E.M.F.'s by the condensing electroscope.

EXERCISES ON CHAPTERS I. AND II. *ELECTRODYNAMICS.*

3. It would become a simple cell.
 4. There would be no action whatever.
 5. See § 151, paragraph above Ex. 5.
 6. With electroscope no difference; with low-resistance galvanometer the big cells give a decidedly greater deflection; with high-resistance galvanometer practically no difference. (See Equation 1, § 138.)
 7. (1) 875 ampère. (2) 10 9375 volts.

8. No difference whatever, because in both cases the E.M.F. and total resistance are the same, and therefore by Ohm's law the current is the same.
9. The north pole will be deflected westward; the reason is that the zinc plate is replaced by platinum, the *direct* E.M.F. of the cell is taken away, and there remains nothing but the back E.M.F., which sends a current the opposite way round the galvanometer coils (see footnote, p. 182).
10. If it branches the *total* current will still be the same throughout, thus if the poles be connected by two wires the current in the *two wires together* will be the same as in the battery; there might, for example, be 2 ampères in one wire, 5 in the other, and 7 in the battery.
14. Cf. Ex. 3, § 151; the two cells are in opposition, and since their E.M.F.'s are equal, the E.M.F. of the combination is nil, hence by Ohm's law no current passes. Cells in opposition will be more fully dealt with in § 161.
15. Yes; the potential of the insulated plate just before lifting the earth plate will be that of the terminal *last touched*, hence the order B A will give the greater divergence.
16. Use a large number, say 50 to 100 cells in series, so as to get the requisite E.M.F.

§ 152. 7300, 26,280,000.

§ 153. 1. 6 H.P. very nearly.

2. £7 10s.

3. 137.5 H.P.; 1230.9 B O T U.

4. 500 volts.

5. 9s. 10d.; about $\frac{3}{4}d$.

§ 154. 1. 162,000.

2. 10 ampères.

§ 157. 2. $1\frac{1}{2}$ watts; $\frac{2}{7\frac{1}{2}}$ H.P.

3. $\frac{1}{2}$ ohm.

4. 900 flashes.

§ 158. The same as in a properly made Daniell, except that there is a great waste of zinc both when the cell is in use and when it is not.

§ 160. 1. $\text{H}_2\text{SO}_4 + \text{H}_2\text{O} = \text{H}_2 + \text{H}_2\text{SO}_4 + \text{O}$.

2. The end of the rod which the current strikes will become coated with a film of finely divided copper and the other end with a film of copper oxide.

§ 161. 1. Yes. A current would flow from the platinum to the copper, thence through the Daniell to the zinc, thence to the Grove zinc, and thence through the Grove back to the platinum.

2. The Daniells give their natural and the Grove its reversed action: in the latter hydrogen or zinc is deposited on the zinc plate, while oxygen is liberated on the platinum plate. .25 ampère; .625 joule.

EXERCISES ON CHAPTERS III. AND IV. : *ELECTRODYNAMICS*

1. (1) No (§ 134); (2) The thin wire gets hotter (§ 155).
4. See § 160.
5. The iron has the higher specific resistance and therefore gets hotter (§§ 135, 155).
6. (hotter part). See § 160 and last par. of § 154.
9. (1) So (§ 134); (2) The thin end gets hotter (§ 155).
11. See § 158. Hydrogen will be given off from both rods, but after the CuSO_4 is poured in it will appear on the zinc rod only.
12. Four-fifths as great.
13. The two together would have no E.M.F. (§ 161), and therefore if *they alone* constitute the circuit there would be no current. If there were other cells in the circuit they would merely offer dead resistance.
14. (1) 1·8. (2) 777·6. (3) 111·1 very nearly; nearly -0174 horse-power.
15. An alternating current is one whose direction undergoes continual rapid reversals; consequently it will not produce electrolysis since every beat reverses the effect of the preceding beat. Any voltmeter will therefore serve as a test.

- § 167. 1. The north pole will move eastwards.
 2. (1) Same effect but much stronger.
 (2) About same as with soft iron.
 (3) Not so strong as soft iron.
3. (i) At whichever end of the spiral the current enters, the north pole of the needle points away from the middle of the tube.
 (ii) Ditto.
- § 168. Whether brass or iron be used, the lines of force run circumferentially and the ring has no effect on the needle, except (in the case of the iron ring) for the inductive action of the needle itself.
- § 169. 1. North pole moves westward.
 2. If the current is strong enough the needle swings round and its North pole points southwards, otherwise it does not move.
 3. The wire is stretched magnetic east and west, and the current flows along it from east to west.
 4. The ring is magnetised circumferentially; to test, it must be cut (§ 92).
 5. (1) Very feeble side polarity (§ 116).
 (2) Magnetised lengthways.
 7. The north pole will move eastward.

EXERCISES ON CHAPTER V.—*ELECTRODYNAMICS*

5. See Maxwell's law.
9. (1) No effect.
 (2) North pole turns to the south.

10. See § 168.
11. Cf. Ex. 5, § 169.
12. Magnetised circumferentially.
13. Place a Kelvin Astatic in the circuit. The reason the current is only momentary is that there is no conducting path from one pole of the battery to the other ; a current merely flows between each pole and the plate thereto connected until the pole and plate acquire the same potential, and then ceases.
15. Hold the wire horizontally parallel to the magnets and midway between them ; if they are of equal strength they will not move.
16. Yes, in all localities the north pole will move upwards.
17. See Maxwell's law.
18. (i) The strength of the electromagnetic field depends only on the current and on the size and form of the spiral, hence the action of the needle is the same in both cases.
(ii) The platinum becomes hotter on account of its higher specific resistance (§ 155).

INDEX.

S. B.—The numbers refer to the sections, not to the pages. The letter *f* indicates a footnote.

A CIDS and Salts	150
Acid line	126
Action, local	148
Agglomerate cell	150
Agonic line	157
Air as an insulator	17
" pressure of	20
Air-bag, analogy to conductor	51
" pressure in	20
Ampere	150
Ampere-hour	150
Anode and cathode	150
Astatic needle	151
galvanometer	179
Attraction, Electrical	1, 17, 19
" Magnetic	81
Axis, Magnetic	119
" of earth	128

B ATTERIES	151
Battery circuit, work and efficiency	157
in	157
Battery cells in opposition	161
" De la Rive's floating	172
Biot's Theorem	64
Birmingham wire gauge	125
Board of Trade Unit	152

C ALORIE	61
Capacity, Specific inductive	58
" Electrostatic	60
Cell, Simple voltaic	135
" defect of	144
" Simon	145
" Poggendorf, or chromic acid	147
" Daniell	148
" Zinc-sulphate form	148
" Grove	149
" Leclanché	150
" Agglomerate	150

Cells in opposition	161
Centimetre	610
Chains, Magnetic	50
Charge	2, 35
" contact	15
" and electrification	20
" induced	45
" Test for amount of	55
" on small area	65
" entirely on outer surface of con- ductor	64
Charts, Magnetic	154
Chromic acid cell	147
Circuit, Magnetic	115
" Electric	154
" Dead and live	154
" Open and closed	155, 157
" Work and power in	155, 157
" Heat in	154
Circumferential magnetization	92
Clockwise and counter-clockwise rota- tion	161
Closed circuit	155, 158
Compass-needle	40
" Mariner's	153
Condensers	79, 84
Combining electroscopes	160
Conductor hollow, Potential of dis- trib in	67, 68
" No inductive dis- placement in	50
" No charge on in- ternal surface of	51
" with charged body inside	57
Conductors, Electrification of	7, 8, 10, 70
" and insulators	7, 8, 11, 12
" Effects of earthing	7, 30
" Lightning	68
Consequent poles	69
Convection, Electric	68
Coulomb	90, 152

N.B.—The numbers refer to the sections, not to the pages. The letter f indicates a footnote.

Current, same at all parts of circuit	134
" Electric	134
" Measurement of	141
" Electrostatic	171
Cutting of lines of force	172

D ANIELI, cell	148
" " , Zinc sulphate form	148
Dead and live circuit	184
Declination	122, 124
Demagnetisation explained by molecular theory	95
Density : <i>see</i> Surface	
Dielectric	28
" surrounding charged conductor	46
" inside hollow conductor	47, 48
" , influence of, on relation between charge and potential	58
Dip, Line of	121
" " " " " " " "	122, 124
" circle	125
Dipping-needle	125
Directivity of uniform field	118
" " , Earth's force	122
Displacement, Inductive	49
" " , None in field	
of uniform potential	50
Drop : <i>see</i> Potential-Drop	

E ARTH, a conductor	11
" , a storehouse of electricity	27
" , a magnet	81, 120
Earth's magnetic field	121
" " " , Intensity of	121, 122
" " " , Inductive action of	180
" magnetism, Elementary representation of	128, 129
Ebonite as an insulator	12
Efficiency	167
Electric circuit : <i>see</i> Circuit	
" field	28
" screens and shadows	53
" cars	153
" light	153
Electrical machines	69
" " , Limit to action of	71
Electricity, Views regarding	4, 11, 26
Electrification, Two kinds of	15, 23, 25
" " , Test for	20, 39
Electrodes	160
Electrodynamics, Meaning of	32f
Electrolysis	160
Electrolyte	160
Electromagnetic polarity, Law of	166
Electromagnetism	165
Electromagnets	84, 108

Electromotive force	137
" " of cell : what it depends on	137, 140
" " and terminal potential-difference	138
" " of series battery	151
Electrophorus	70
Electroscope, Pith-ball	6
" , Gold-leaf, description of	34
" " , principle of action	35, 36
" " , Potential of	35, 36, 38
" " , how to charge freely	37
" " , how to charge by induction	45
" " , Use of, to determine existence and character of charge	39
" " , Use of, to test strength of potential	40
" " , Use of, to test amount of charge	55
" " , Use of, to check Poisson's principle	44
" " , Screening of	53
" " , Condensing	140
Electrostatics, Meaning of	32f
Emptying out	51
Energy	61
" , Chemical potential	61, 132
" , Electrical	61, 62, 132
" , Source and sink of	132, 134
Equator, Magnetic (of magnet)	88
" " (of Earth)	126
Erg	61
Excess and deficit	26

F ARADAY'S ice-pail	52
Field, Electric	28
Field, Magnetic	104
" " , Force in	105
" " , Exploration of	106
" " , Internal	113
" " , Uniform	118
" " , of Earth	121
Flux, Magnetic	112, 114
" " , Mutual magnetic action in terms of	172
Foot-pound	61
Force, Magnetic	94, 105
" " lines of	107, 108, 109
" " tubes of	112
Forces, their mutuality	3

N.B.—The numbers refer to the sections, not to the pages. The letter j indicates a sub-note.

Free charge	5	Kilowatt	113
" potential	41	Kinetic energy	43
Frictional order	24		
" machines	69		
G ALVANOMETER, Tangent ..	141	L ATERAL polarity	69
" " Single coil	141	" " magnetisation	69
" " Multiple coil	141	Leakage, Magnetic	133
" " High and low resistance	142	Least resistance, Principle of	146
" " Astatic	170	Leakage coil	150
Galvanoscope	141, 142	Leyden jar	72, 74
Generator, Electric	134	Lightning conductor	66
Granhin's hypothesis	146	Lines of force	105, 169
Grove cell	149	" " " Number of	117
		" " " Internal	113
		" " " Cutting of	117
		Lines of induction	113
		Lines, Isoline	176
		" " Isogonic	127
		Live and dead circuit	154
		Local action	154
H EAAT, its effect on magnetisation	102	M AGNETIC: see separate headings—	
" generated in chemical action	132	<i>e.g.</i> chains, poles, etc.	
" in wire	154	Magnet, Simple	86, 113
Hemispheres, Magnetic	126	Magnets and magnetic substances	79
Hollow conductor: see Conductor		" " Permanent and electric	84
Horizontal intensity of earth's field, ...	122	Magnetisation, Test for	79
Horse-power and Watt	153	" " Internal and external	92
		" " Circumferential	92
		" " Irregular	93
		" " Lateral	93
		" " Explanation of, by mo-	
		"lecular theory	95
		" " Methods of	101
		" " Effect of heat and agita-	
		"tion on	107
		Magnetism, a molecular property	89
		" " Molecular theory of	91
		Martini's compass	124
		Maxwell's law	177
		Meridian, Magnetic	127
		Molecular rigidity	96
		Molecular theory	89, 91, 95
		" " Experiment to illu-	
		"strate	103
		Mutuality of forces	9
I CE-PAIL, Faraday's	52	N EEDELE, Magnetic	80
" Inclination	122, 124	" " " under joint in-	
Induced potential	41	"fluence of earth	
" charge	45	"and magnet	179
" polarity, Law of	85, 110	" " " Astatic	121
Induction, Electrostatic	5, 41, 45, & c.	" " " Compound	121
" " Magnetic	83	Neutral bar, effect of introducing into	
" " " explained by mo-		"magnetic field	154
"lecular theory	100	Neutral bodies, ...	2, 74
" " " tubes of	113	" " why attracted	66
Inductive displacement	49	Number of lines of force	113
" " none in field of			
"uniform po-			
"tential	50		
" capacity, Specific	58		
" action of earth's field, ...	130		
Inductivity, Specific	58		
Insulators	7, 8, 11, 13		
Intensity of magnetic field	111		
" " earth's	121, 122		
Internal magnetisation	92		
" field	113		
Iron and steel	84		
Irregular magnetisation	93		
Isoline lines	126		
Isogonic	127		
J AR, Leyden	72-76		
" Joule	41		
Joule's law	154		
K ATHODE and anode	160		
" Keepers	98		

N.B.—The numbers refer to the sections, not to the pages. The letter f indicates a footnote.

O ERSTED'S experiment	109
Ohm	136
Ohm's law	136
" " , application to external, internal, and complete circuit	136
" " , application to series battery	151
One-fluid theory	26, 27
Open circuit	135, 138
Opposition, Cells in	161
Order, Frictional	24

P ERMEABILITY, Magnetic	115, 116
Plate machine	69
Points, Action of	68
Poisson's principle	32
Polarity, Magnetic	80
" " , Test for	82
" " , induced, Law of	85
" " " " , in terms of lines of force	110
" " , Reversal by induction	87
" " , Distribution in magnets	88
" " , Lateral and terminal	88
" " , electromagnetic, Law of	106
" " " " " , application to straight wire	169
Poles, Consequent	80
" " , Magnetic	80
" " , precise meaning	118
" " , of earth	126, 128
" " , of cell	134
Potential	31, 32, 33, <i>et seq.</i>
" " , High and low	33
" " , Strong and weak	33
" " , Test for strength of	40
" " , Free and induced	41
" " " " , Coexistence of	42
" " , and change	43, 56, 57, 58, 59
" " , gradient	46, 134
" " , its relation to surface density	67
" " , uniform, Field of	47, 48, 50
" " , influenced by dielectric	58
" " " " , neighbouring conductor ..	59
" " , energy	61
" " , analogy to temperature and level	63
" " , difference	134, 136
" " " , terminal	137, 138
" " , drop	136
" " " , internal of cell	139
Power in electric circuit	153
Pressure of air	29
" " , Electrical	31
Principle, Poisson's	32

Principle of least reluctance	116
Proof plane	65
" " , cone	65
Pump, Electric	154

Q UANTITY, Unit of	26, 152
---------------------------------	---------

R ELUCTANCE, Magnetic	116
" " , Principle of least ..	116
Repulsion, Electrical	16, 17, 19
" " , Magnetic	81
Resistance	135
" " , External and internal	135
" " , of cell: what it depends on	135, 143
" " , of wire	135
" " , Specific	135
" " , of series battery	151
" " , Influence of temperature on	156
Retentivity, Magnetic	97
Rigidity, Molecular	96
Rotation, Clockwise and counter-clockwise	163

S ALTS	159
Saturation, Magnetic	94
Screens, Electric	63
" " , Magnetic	117
Shadows, Electric	58
Simple magnet	88, 115
" " , cell	133
" " " , Defect of	144
Smee cell	145
Spark, Electric	67
Specific inductivity	58
" " , inductive capacity	58
Spirals, right and left-handed	164
" " , Electromagnetic polarity of ..	167
Steel	84
" " , Cast-dynamo	84
Surface density	66
" " , Relation of, to potential-gradient	67
Susceptibility, Magnetic	115

T EMPERATURE and potential, Analogy of	63
Temperature, Rise of, in wire	155
" " , effect on resistance	156
Terminal potential-difference	138
Test for electrification	20
" " , strength of potential	40
" " , amount of charge	55
" " , electric density	65
Theory, One and two fluid	26, 27

EXAMINATION PAPERS
IN FIRST STAGE MAGNETISM AND ELECTRICITY.
(Set by the Board of Education, Secondary Branch.)

1900.

Magnetism.

1. How would you place a rod of soft iron for it (i) not to be magnetised, (ii) to be magnetised as much as possible, along its length by the earth's inductive action? Give your reasons. (12)

2. Describe and explain the movement of a small compass needle placed in the middle of a horizontal circle round which the north pole of a long vertical magnet is carried, which produces at the centre of the circle a magnetic field less strong than that of the earth. (12)

3. Two rods of the same size, one of soft iron and the other of hard steel, are each rubbed from end to end with one pole of a strong bar magnet. How will the rods affect a compass needle to which they are successively brought near? (12)

4. Two equal magnets of the same strength are placed on a horizontal table parallel to each other and perpendicular to the line joining their centres with similar poles in opposite directions. What changes would take place in the magnetic field produced by them close to the surface of the table if they were gradually moved parallel to themselves until they were in contact along the whole of their lengths? Give diagrams showing how your statements might be tested by means of iron filings. (13)

Frictional Electricity.

5. Given two insulated metal spheres *A* and *B*, of which *A* is charged with positive electricity and *B* is uncharged, show how a positive charge may be communicated to a gold-leaf electroscope by means of *A* and *B* without *A* losing any of its charge. (13)

6. An excited rod of sealing-wax is held about one inch from the wall of a room which may be regarded as a conductor. A proof plane is made to touch the part of the wall nearest the sealing-wax and is then carefully removed to a distance. What is now the electric state of the proof plane as regards charge and potential? (12)

7. Explain the action of the points on the prime conductor of an electrical machine. What experimental result can you quote in favour of your explanation? (12)

8. The internal coating of an insulated Leyden jar is charged to a positive potential by an electrical machine. What is the condition of the outer coating as to charge and potential? and what change, if any, do these undergo if the outer coating is put to earth while the machine is still in action? (12)

9. The end of a long rod of sealing-wax and a piece of flannel supported by an insulating handle are held inside a metal vessel placed on the cap of a gold-leaf electroscope. Describe and explain the behaviour of the leaves when the sealing-wax and flannel are rubbed together, and then first the sealing-wax and secondly the flannel is withdrawn from the vessel, which has not been touched by either of them during the operations. (16)

Voltairic Electricity.

10. How would you prove experimentally that the electrical condition is not the same for two copper wires connected respectively with a piece of zinc and a piece of platinum, when the platinum and zinc both dip in the same vessel of sulphuric acid? (12)

11. An electric current is passed through a copper wire which is coiled in a helix. What changes are thereby produced in the condition of the wire? (12)

12. The ends of a brass rod on which a steel ring has been slipped are joined to the poles of a voltaic battery. Is the steel ring magnetised by the passage of the current through the rod? How will you test whether it is or not? (12)

13. The poles of a voltaic battery are joined to the ends of a chain composed of alternate links of iron and copper. It is noticed that the iron links become better than the copper links. How do you explain this? (12)

14. An electric current passes through a horizontal wire which runs north and south, and over which a small compass is placed. Draw and explain a diagram illustrating the conditions which determine the position taken up by the needle. (12)

Answers.—1. (1) Perpendicular to, (2) in the line of, dip.

6. Both are positive. 8. (1) No charge, potential positive; (2) potential becomes zero, charge negative.

9. (1) No result; (2) the leaves diverge with positive electricity; (3) collapse. 11. (1) It behaves as a magnet; (2) is heated.

12. (1) Yes. (2) Break it into separate links.

13. The iron links have the greater resistance,

1903.

Magnetism.

1. A bar magnet lying on a table about a foot from a compass needle produces a certain deflection of the needle. How is the deflection altered (if at all) when an iron bar the same size and shape as the magnet is placed on the top of the magnet? (12)

2. A glass tube AB nearly full of steel filings is stroked from the end A to B by the north pole of a strong magnet. What will be the effect produced when AB is brought near a freely suspended magnet? What change will be produced by shaking the tube? (12)

3. A tall iron mast is just forward of the compass of a wooden ship; explain how this will affect the direction of the compass when the ship is sailing (1) to the east, (2) to the north, in the northern hemisphere. (12)

4. In England a dip needle swinging in a plane perpendicular to the magnetic meridian returns to a vertical position when deflected from it, but does not do so at the magnetic equator. Explain this. (12)

Frictional Electricity.

5. How would you show that a piece of metal when rubbed with flannel is charged with electricity, and how would you test whether the charge is positive or negative? (12)

6. A charged insulated conductor A is surrounded by a closed metallic box; what experiment would you make to show that the charge on the inside of the box is equal and opposite to that on the conductor? (12)

7. The case surrounding the gold leaves of an electroscope is made of metal with glass windows. When the instrument is placed on an insulating stand and the case charged with electricity, is there any divergence of the leaves? When the instrument is placed inside an insulated and charged metal vessel, is there any divergence? Give reasons for your answers. (13)

8. Explain what is meant by difference of potential. How are the charge and the potential of an insulated body altered by bringing a positive charge near it? (12)

9. A Leyden jar, charged in the ordinary way, is placed on an insulating stand. What effect is experienced by a person touching the knob of the jar? Explain why the jar is not entirely discharged by the contact. (12)

Voltai Electricity.

10. How is polarisation prevented in a Daniell cell? How does a large Daniell cell differ from a small one in respect of (1) electromotive force, (2) resistance? (12)

11. What experiment would you make to determine whether the current through an incandescent lamp was alternating or continuous? (12)

12. A straight wire carrying a current is placed over a thin rod of iron (1) parallel to the iron, (2) at right angles to it. Is the iron in either case magnetised? Give reasons. (12)

13. The resistance of a battery is 1 ohm, and the current through a wire AB , whose resistance is 5 ohms and which joins the terminals of the battery is 1 ampère. If AB is replaced by another wire CD , the current is $\frac{1}{4}$ th of an ampère. What is the resistance of CD ? (12)

14. One yard of thin, and one yard of thick copper wire are joined in series with a battery of Daniell cells. Is there any difference between (1) the currents in, (2) the temperatures of, the two wires? (12)

Answers.—1. Deflection reduced. 3. (1) North-seeking pole deflected west. (2) Needle either unaffected or reversed. 7. (1) Yes, (2) No. 12. (1) No; (2) Yes. 13. 200 ohms. 14. (1) No difference in the currents; (2) The thin wire is hotter.

1904.

Magnetism.

1. Explain what is meant by *magnetic induction* or *influence*. Give a sketch showing how the lines of magnetic force in a room would be disturbed by the introduction of a large vertical pillar of soft iron. (12)

2. An iron rod is very feebly magnetized. When its north pole is two inches from the north pole of a compass needle, repulsion takes place. When the distance is reduced to half an inch, the poles attract each other. Explain this. (13)

3. A sensitive compass needle is placed at a distance of 2 feet from the centre of a bar magnet and equidistant from either pole. What is the effect on the needle (1) when the bar lies along the magnetic meridian, (2) when the bar is perpendicular to the meridian? (12)

4. A dip needle in England is loaded so that when disturbed it oscillates about a horizontal position. How will it behave when taken to the equator if the load is not altered? (12)

Frictional Electricity.

5. How could you show (1) that the potential at a point on the inside of a conductor is the same as that at a point on the outside, (2) that there is no electricity inside a nearly closed conductor when the outside is highly charged? (12)

6. The caps of two gold-leaf electroscopes are connected—one to the inner, the other to the outer, coating of an insulated Leyden jar. How are the leaves affected when a positive charge is communicated to the inner coating of the jar? (12)

7. Radium shoots out continually both positively and negatively electrified particles. What experiment could you make to test whether the quantities of positive and negative electricity simultaneously produced by radium are equal? (13)

8. Describe the essential points in the construction of a sensitive gold-leaf electroscope. (11)

9. Describe carefully the construction and action of a simple form of machine depending on friction for generating and collecting positive electricity. What becomes of the negative electricity simultaneously produced? (12)

Voltain Electricity.

10. Describe a Daniell cell, and explain the chemical changes which take place in it when in action. What are its defects for ordinary purposes, such as ringing electric bells? (12)

11. What are the essential points in the construction of a tangent galvanometer? How should the instrument be adjusted? (12)

12. Describe a form of apparatus for decomposing water by means of an electric current. How would the result be affected if the electrodes were made of copper instead of platinum? (12)

13. A magnet which can turn freely about a vertical axis is placed near a long vertical wire carrying a large electric current. How will the magnet act, and how can you determine the direction of the current? (12)

14. A current is sent through a piece of fine wire by a voltain cell, the resistance of which is very small compared with that of the wire. How will the heat produced be altered if the length of the wire is halved? (12)

Answers.—4. South-seeking pole dips down.

14. Twice as much heat is produced.

1905.*Magnetism.*

1. A piece of iron when brought near to a small compass needle attracts one pole and repels the other; how would you ascertain whether it was permanently magnetised or only temporarily magnetised by the earth's magnetic field? (12)
2. Sketch the lines of force of a bar magnet, with an equal bar of soft iron laid across its N. pole so as to form a T. (13)
3. A horseshoe magnet laid on the table near a compass needle produces a deflection of the latter. When the keeper of the magnet is placed near the poles, but not touching them, the deflection is diminished. How do you explain this? (12)
4. The beam of a balance is made of iron. If the balance is placed so that the beam vibrates in a plane at right angles to the magnetic meridian, the beam is horizontal when equal weights are placed in the scale-pan. What will happen when the balance is turned so that the iron beam swings in the magnetic meridian? (12)

Frictional Electricity.

5. How would you show, by means of a condensing electroscope, that the poles of a voltaic battery are oppositely charged? (13)
6. When a charged glass rod is brought near to an electroscope the leaves diverge, and fall together again when the rod is withdrawn. If a needle is placed on the cap of the electroscope, with the point projecting from it, and the experiment is repeated, the leaves diverge on approach of the glass rod, but remain divergent when the rod is taken away. Explain this. (12)
7. A deep metal cylinder open at the top is placed on an insulating stand and charged with negative electricity: a metal sphere supported by an insulating silk thread is put in contact (a) with the outside, (b) with the inside of the can, and then brought close up to a positively charged gold leaf electroscope. State and explain the effect produced on the electroscope in the two cases. (12).

8. A Leyden jar held in the hand is charged from one pole of an electric machine, the other pole being earthed. What difference will it make if the person holding the jar stands (1) on an insulating stool, (2) on the ground? (12)

9. Explain what is meant by electrostatic induction.

Two small light pith balls are in contact, and are supported by separate threads. A charged glass rod is brought in the neighbourhood of the balls. What will happen (a) when the threads are wet and conducting, (b) when they are dry and insulating? (12)

Voltal Electricity.

10. In what respects does the current produced by a voltaic cell differ from the discharge of an electric machine? What do you understand by the strength of a current, and by what effects may the strength be measured? (11)
11. Describe the construction of, and the chemical action which takes place in, a Leclanché cell. Is this a constant cell? If not, why not? (12)
12. Does a straight copper wire through which an electric current flows attract or repel a magnetic pole? How do you explain what happens when such a wire is plunged into iron filings? (13)
13. An electric current is passed through a platinum wire and a copper wire of the same size, arranged in series. If the strength of the current is sufficiently increased, the platinum becomes red-hot while the copper remains dark. Explain this. (12)
14. Show that a galvanometer with a single needle may be made more sensitive by placing a magnet in a suitable position in its neighbourhood. Give a sketch showing how you would mount the magnet so that by moving the magnet the sensitiveness may easily be altered; indicate the position of the poles of the magnet when the sensitiveness of the instrument is as great as possible. (13)

The Organized Science Series:
FOR THE SCIENCE AND ART EXAMINATIONS
OF THE
BOARD OF EDUCATION.

GENERAL EDITOR. — WM. BRIGGS, LL.D., D.C.L., M.A., B.Sc.

FOR THE SECOND STAGE.

- V. **Second Stage Mathematics** (the additional Algebra and Euclid, with the Trigonometry required). *Third Edition.* 3s. 6d.
- VI.A. **Second Stage Mechanics (Solids).** *Third Edition, Revised and Enlarged.* Part I. DYNAMICS. Part II. STATICS. 3s. 6d. each Volume.
- VIII.C. **Second Stage Heat.** *Third Edition.* 3s. 6d.
- IX. **Second Stage Magnetism and Electricity.** *Second Edition, Revised and Enlarged.* 3s. 6d.
- Technical Electricity. 4s. 6d.
- X. **Second Stage Inorganic Chemistry (Theoretical).** *Third Edition, Revised and Enlarged.* 4s. 6d.
- XI.P. **Second Stage Inorganic Chemistry (Practical).** *Second Edition, Revised and Enlarged.* 2s.
- XI.P. **Systematic Practical Organic Chemistry.** 1s. 6d.
- XVII. **Second Stage Botany.** 3s. 6d.
- XX. and XXI.B. **Modern Navigation.** 6s. 6d.
- XXV. **Second Stage Hygiene.** *Second Edition.* 3s. 6d.

LONDON: W. B. CLIVE, 157 DRURY LANE, W.C.

THOMAS LAURIE, 13, Paternoster Row, London, E.C.

JUDE'S MAGNETISM & ELECTRICITY (First Stage)

AND

SCHOOL MAGNETISM & ELECTRICITY.

THE following Special Apparatus, required for experiments in these books, can be obtained of THOMAS LAURIE, 13, Paternoster Row, London. Several of the instruments are of original design and are registered.

MAGNETISM.

BARS Bars of Steel and Iron, per doz., Short 4", Long 9". Thin Magnetised Bars, about 4 inches long by 1/16th inch diameter with hooks, per doz., 1/6.

RINGS Iron and Steel Rings (Fig. 1), No. 1 each, 1/6.

EXPLORER (Fig. 62), each, 1/4.

STEEL FILINGS in tube, loosely packed, each, 1/6.

FRICTIONAL ELECTRICITY.

AIR BAG of India Rubber (Fig. 6) and pressure gauge, each, 1/6.

CONDENSER for use with Electroscopes (Fig. 61), £1.

CONDUCTORS Assortment on Ebonite legs (Figs. 5, 10, 12, 13), Set of five, £3 10.

COPPER Circular Sheet, about 12 inches diameter, 1/16th inch thick, 1/2. Ebonite Handle, 1/6.

COPPER WIRE uncoated. Hank on No. 20 B.W.G., 1/4.

ELECTROSCOPE, Special Patent (Fig. 7), 1/6.

EBONITE Sticks of Ebonite, 1/6.

HANDLE Ebonite Handle with screw (Fig. 4), each, 4d.

KNOWTEST Gutta Serena, covered copper wire, No. 24 B.W.G., with small brass ends, soldered, 1/4.

INDIA RUBBER Sheet, 2 1/2 inches thick, and 9 by 6 inches square, 1/6.

PROOF PLANE and proof cone (Fig. 20), on Ebonite Handle, 1/6.

POIS Assortment of tin pots, typical sizes, per set, 4d.

TONGS Insulating Tong, each, 1/6.

VOLTAIC ELECTRICITY.

BOX BATTERY, with Leclanche cells (p. 27), 4 pints in box, £1 10.

CELLS Leclanche or Agglomerate cells, 2 pints each, 4d.

COPPER STRIP with core (Fig. 125), 1/6.

GALVANOMETER, Simple Tangent (Fig. 123). High and Low Resistance, £1.

RINGS Iron and Brass 4 inch rings, wound with close coils of enamel or silk, covered wire and terminating in coupling screws, 1/6.

ROTARY contrivance (Fig. 124), 1/6.

SPIRALS Pair of right and left handed, mounted on wooden frame, 1/6.

VOLTAMETER with platinum plates, 1/6.

JUDE'S DOUBLE-LEAF ELECTROSCOPE (Patented). This instrument enables the fundamental principles of electrostatics to be demonstrated to a class with great clearness. Price 17/6. *Illustrated Prospectus on application.*

JUDE'S MULTIPLEX CONNECTOR (Patented). Enabling cells to be expeditiously connected either in series, arc, or compound circuit. Price 6/6. *Illustrated Prospectus on application.*

JUDE'S GALVANOMETER OR GALVANOSCOPE, High and Low Resistance. Enabling the effects of coupling cells to be demonstrated in a few moments. Price 20/-. *Illustrated Prospectus on application.*

THOMAS LAURIE, 13, Paternoster Row, London, E.C.

THOMAS LAURIE, Scientific Apparatus Maker.

**NEW AND IMPROVED APPARATUS
FOR TEACHING**

MAGNETISM & ELECTRICITY.

(Patent)

Invented by R. H. JUDE, M.A., D.Sc., Head of Mathematical and Physical Department, Rutherford College, Newcastle-on-Tyne; Author of "First Stage Electricity and Magnetism," and "Physics: Experimental and Theoretical."

These Inventions by Dr. Jude are the fruit of much thought, and of years of experiment, on the part of a successful practical teacher and writer. They will be found to effect a great saving in the time and work of both teacher and class.



JUDE'S DOUBLE-LEAF ELECTROSCOPE

Price 17/6.

This Instrument supplies the long felt want of a really good Electroscope for the Lecture Table. It enables all the most important principles of Electrostatics to be demonstrated with great clearness; its working is thoroughly reliable, it requires no drying or heating, and contains no sulphuric acid or other chemicals. It can also be well seen from a distance by a large class.

JUDE'S SINGLE-LEAF ELECTROSCOPE

Price 30/-

This Instrument is of advantage for certain special experiments. It consists of a single gold leaf suspended between two copper plates A and B; when A's potential is higher than B's the leaf moves from A towards B, and vice versa.

JUDE'S GALVANOMETER or GALVANOSCOPE

(High and Low Resistance). Price 20/-

The Instrument is conveniently adapted for use with the Multiplex Connector (which see), as it enables the effects of coupling cells in different ways, both with high and low external resistance, to be experimentally demonstrated in a few moments.

JUDE'S MULTIPLEX CONNECTOR

Price £3.

This is an original invention for enabling cells to be expeditiously connected either in series, or in compound circuit.

An explanatory illustrated prospectus of the above four inventions, and additional apparatus for teaching Electricity, may be obtained of the sole maker,

THOMAS LAURIE, 13, Paternoster Row, London.

SCIENCE AND ART EXAMINATIONS

(BOARD OF EDUCATION).

SECOND STAGE.

V.—**Mathematics, Second Stage.** Being the Additional Algebra and Euclid with the Trigonometry required. Edited by Dr. WM. BRIGGS, M.A., F.R.A.S. *Third Edition.* 3s. 6d.

"To students preparing for the second stage it will be useful to have the three subjects so fully treated, and yet within the limits of a single volume."—*Journal of Education.*

"The range of the subjects, and the handling of them both seem thoroughly suited to the requirements of the syllabus."—*Guardian.*

VIa.—**Mechanics, Second Stage.** By DR. WM. BRIGGS, M.A., B.Sc., F.R.A.S., and G. H. BRYAN, Sc.D., M.A., F.R.S. Vol. I., DYNAMICS. *Third Edition, Revised and Enlarged.* 3s. 6d.

"The student who wishes to face the examination with a cheerful countenance should master this well-written *vade mecum*, than which no better treatise has come under our notice."—*Practical Teacher.*

VIa.—**Mechanics, Second Stage.** By DR. WM. BRIGGS, M.A., B.Sc., F.R.A.S., and G. H. BRYAN, Sc.D., M.A., F.R.S. Vol. II., STATICS. *Third Edition, Revised and Enlarged.* 3s. 6d.

"This is a welcome addition to our text-books on statics. The treatment is sound, clear, and interesting, and the familiar old proofs are simplified and improved."—*Journal of Education.*

"The book is thoroughly practical, the principles and demonstrations are remarkably clear."—*Schoolmaster.*

VIIIc.—**Heat, Second Stage.** By R. WALLACE STEWART, D.Sc. Lond. *Third Edition.* 3s. 6d.

"Students will find this book suitable for their purpose. The statements are accurate, the style clear, and the subject-matter up to date."—*Education.*

IX.—**Magnetism and Electricity, Second Stage.** By R. WALLACE STEWART, D.Sc. Lond. *Second Edition, Revised and Enlarged.* 3s. 6d.

"The numerical exercises set are excellent, and we can recommend the book to candidates for the Second Stage Board of Education Examination."—*Electrician.*

Physics
Elect
J

Jude, R.H.

82935
First stage magnetism and electricity.

UNIVERSITY OF TORONTO
LIBRARY

Do not
remove
the card
from this
Pocket.

Acme Library Card Pocket
Under Pat. "Ref. Index File."
Made by LIBRARY BUREAU

NS

G. H.
Dr. Wm.
4s. 6d.
is them-
ence as a

aker.
nd Stage.
nd R. W.
prof. 2s.
is especially

atic analysis.

. GEORGE,
bus is carried
nd the book."

erson, M.A.,
excellent."

ience, and is

st and
nd pos-
tion of
wish to

B.Sc.,
2s. 6d.
further
ext by

